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Commissioning and Quality Assurance of Computerized Planning Systems for Radiation Treatment of Cancer

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COMMISSIONING AND QUALITY ASSURANCE OF COMPUTERIZED PLANNING SYSTEMS FOR RADIATION TREATMENT OF CANCER

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FOREWORD

The radiation therapy treatment planning process is complicated, has many steps and is potentially a high risk procedure, as it involves the handling of multiple sources of information and the interaction of different professional groups all dedicated to treating cancer patients with radiation. The IAEA has analysed a series of accidental exposures in radiotherapy to learn about methods of preventing future occurrences. This analysis included a review of accidents that occurred owing to improper, or lack of, commissioning and appropriate quality control procedures for computerized treatment planning systems (TPSs) at purchase, commissioning or during the use of the equipment. The IAEA report Investigation of an Accidental Exposure of Radiotherapy Patients in Panama, published in 2001, presented a further example of very significant errors related to the improper use of TPSs that affected cancer patients in Panama.

Quality assurance (QA) in the radiation therapy treatment planning process is essential for minimizing the possibility of accidental exposure. It is of special importance to support hospitals in Member States in developing procedures for the commissioning and QA of computerized TPSs. The relatively low cost of today's equipment has made TPSs widely available in industrialized and developing countries, but with the exception of a few national recommendations for QA in North America and western Europe, no publications are available for professionals to follow to check their TPSs. Responding to the need to develop an IAEA publication with such recommendations, a group of experts (J. Van Dyk (Canada), J.-C. Rosenwald (France), B. Fraass (United States of America), J. Cramb (Australia) and F. Ionescu-Farca (Switzerland)) was appointed in 1999 and prepared such a document during 2000–2002. The main issues that deserve attention in QA protocols for TPSs were discussed at length during two Consultants Meetings held in 1999 and 2000 in Vienna. These meetings covered the range of ancillary equipment from that available in poorly equipped hospitals to that required for the sophisticated and modern treatment techniques available in better equiped facilities. A detailed outline for a publication with sections that deal with both external beam radiotherapy and brachytherapy, describing tolerances and errors, resource requirements for QA, issues to be considered at purchase, acceptance tests, commissioning and the continuing QA process and its management, was developed, and the final report was prepared for publication as this technical report.

Owing to the complexity of the treatment planning process, this report does not provide a simple protocol that can be followed step by step by the user at a radiotherapy centre for the commissioning and QA of a specific TPS. Instead, this report provides guidance on the tests and procedures that should be considered. Specific examples of tests and procedures are given, and the medical physicist may have to modify these depending on his or her TPS, on the irradiation facilities available or on the specific treatment techniques to be employed. It must be emphasized that the rationale for the multiple tests described in this report is related to the four major issues of a well structured QA programme in computerized treatment planning, namely education, verification, documentation and communication. The implementation of such a programme will ensure confidence that each patient will receive the radiation treatment as planned and that no errors will occur in the process of using the TPS. This report is addressed to all those individuals who participate in any aspect of TPS commissioning and its QA programme.

The IAEA wishes to express its thanks to all authors and reviewers of this report as listed in the Contributors to Drafting and Review section at the end of this report. The editorial contribution of J. Van Dyk is especially acknowledged.

The IAEA staff members responsible for the preparation of this report were P. Andreo, J. Izewska, K. Shortt and S. Vatnitsky of the Division of Human Health.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Cancer is a significant health care problem; on average about half of all cancer patients are treated with radiation therapy worldwide. This mode of treatment uses complex technology that involves megavoltage radiation that, if not handled with the greatest of care, could lead to significant patient treatment errors and exposures of staff. Recent years have seen a rapid development in the technology of radiation oncology. One of the prime factors contributing to this rapid development has been the evolution of computer technology and its applications in: (a) patient diagnosis using sophisticated computerized diagnostic imaging equipment; (b) the process of radiation treatment planning using computerized radiation treatment planning systems (TPSs) that are capable of using data from diagnostic imagers; and (c) radiation dose delivery using relatively simple ^{60}Co machines or complex linear accelerators with computer controlled delivery systems including multileaf collimators (MLCs) for field shaping, possibly in a dynamic mode while the beam is on. The radiation treatment process involves the application of some or all of these technologies to provide the desired dose to the target volume while minimizing exposure to adjacent normal tissues.

While dose computational equipment was available as early as 1951 [1], more generalized treatment planning calculations evolved, including under the sponsorship of the IAEA [2], in the 1960s that made use of time sharing systems to develop atlases of isodose distributions for general use. In the 1970s and 1980s treatment planning computers became more specialized and readily available to individual radiation therapy centres. As computer technology evolved and became more compact so did TPSs, while at the same time dose calculation algorithms and image display capabilities became more sophisticated. While there is a substantial variation in capabilities, today's treatment planning computers have become readily available to virtually all radiation treatment centres. Many of these systems have both complex three dimensional (3-D) image manipulation and dose calculation capabilities.

The purpose of this report is to describe the commissioning and quality assurance (QA) procedures that should be used with modern TPSs.

1.2. TARGET AUDIENCE

This report is aimed at all individuals who participate in any aspect of TPS commissioning and QA. In general, such individuals are medical physicists with specialized radiation oncology physics training and practical clinical experience. This report is especially relevant to those individuals who have a major responsibility for the TPSs in his or her department.

1.3. CLINICAL USE OF TREATMENT PLANNING SYSTEMS

The radiation treatment planning process is complex and involves multiple steps and a number of technologies. The first step in the process includes the derivation of patient anatomical information. This information is then used to determine the location of the tumour and important normal tissues that could be affected by the radiation treatment. The TPS is used to determine the dose distribution that will result in the body from selected incident beams. The optimum beam arrangement that will provide adequate coverage of the malignant tissues while minimizing the dose to critical normal tissues will be selected. To do this, information is required either in the form of simple external patient contours or more detailed patient image information that can be derived from computed tomography (CT) scans or other imaging modalities such as magnetic resonance imaging (MRI) or, more recently, positron emission tomography (PET). Once the beam arrangement is selected, the radiation dose is calculated throughout the volume of interest by the TPS. Having the dose distribution, the treatment planner or the physician can decide on its adequacy and determine whether further addition of beams or modification of beam direction, weighting or shaping are required to improve the treatment plan. Using such an iterative process, an optimized radiation treatment plan is developed. The TPS is further used for determining the length of time or the number of monitor units (MUs) required for each beam incident on the patient.

In a similar fashion, TPSs are also applied in the context of brachytherapy, which uses radioactive sources within applicators placed inside a body cavity or inserted directly within the malignant volume. For brachytherapy, either the dose rate or the duration of treatment is determined, or, for permanent implants, the total dose delivered to a relevant volume is calculated. Optimization then will lead to the selection of the appropriate activity of radioactive seeds to be used in a given implant.

The TPS also provides a permanent record of the dose delivered to the patient. This information is potentially needed in the event of further treatments or for retrospective or prospective clinical studies.

1.4. COMMON ERRORS

As part of the implementation of sophisticated radiation therapy technology into clinical practice, it is important to recognize that such technology has inherent risks if not handled and administered properly. Recent reviews of accidental exposures in radiation therapy [3, 4] provide some clear lessons that should be learned by professionals involved in prescribing, calculating and delivering radiation treatments. A recent IAEA report [4] describes 92 accidental exposures in radiation therapy and highlights some lessons that can be learned from a review of these accidental exposures. Table 1 summarizes 26 accidental exposures that relate to the radiation treatment planning process. These findings are listed in some detail in order to provide an awareness of the types of error that can occur and to emphasize the importance of proper commissioning and QA procedures for the implementation and use of radiation treatment planning technology.

The International Commission on Radiological Protection (ICRP) has produced a report on the prevention of accidental exposures to patients undergoing radiation therapy [5]. This report describes a series of severe accidents for illustrative purposes, discusses the causes and contributory factors of these events, summarizes the sometimes devastating consequences and provides recommendations on the prevention of such events. For the accidents associated with TPSs, it was concluded that major contributory factors include:

(a) A lack of understanding of the TPS;
(b) A lack of appropriate commissioning (no comprehensive tests);
(c) A lack of independent calculation checks.

A further and more recent example of very significant treatment errors occurred in 2000 and 2001 and affected the lives of patients in Panama [6]. The error related to the method of shielding block entry into the TPS and the resultant MU calculation. This error occurred for 28 patients, 12 of whom have since died, with five of these deaths being a direct result of the treatment error. The expert panel that reviewed these accidents concluded that a combination of treatment planning computer error and lack of a manual MU calculation check resulted in significant patient overexposures. The exposures were greater

TABLE 1. ACCIDENTAL EXPOSURES THAT RELATE TO THE RADIATION TREATMENT PROCESS AS SUMMARIZED IN REF. [4]

Event[a]	Description	Comments
External treatment planning: Treatment planning, patient set-up and treatment		
21	Inconsistent sets of basic data	Lack of effective procedures and documentation: two inconsistent sets of data Incorrect data used without verification
22	Incorrect data for tissue maximum ratios	Lack of adequate verification: tables not verified against published data
23	Insufficient understanding of the TPS algorithm	Incorrect understanding of the use of the wedge factor by the TPS: incomplete validation of the TPS Lack of effective procedures and documentation: no manual checking of computer calculations
24	Incorrect basic data in the TPS	Inadequate commissioning of the TPS Inadequate transfer of information to newly appointed staff Lack of effective procedures and documentation: no independent check of treatment plans
25	Incorrect depth dose data	Insufficient training and/or expertise: known discrepancy was not resolved Lack of effective procedures and documentation: incorrect commissioning
26	Incorrect calculation of treatment times	Lack of effective procedures and documentation: incorrect tables accepted for use Lack of an independent check of the database No independent check of treatment time calculations
27	Misapplication of distance correction	Insufficient training and/or expertise: training should include a specific TPS Lack of effective procedures and documentation: incorrect commissioning of the treatment planning computer with a poor understanding of the algorithm Lack of independent checking procedures
28	Incorrect calculation of the inverse square law	Insufficient awareness of the actual treatment source to surface distance (SSD) Lack of an independent check of the treatment plan Lack of effective procedures and documentation: treatment times were not checked

TABLE 1. ACCIDENTAL EXPOSURES THAT RELATE TO THE RADIATION TREATMENT PROCESS AS SUMMARIZED IN REF. [4] (cont.)

Event[a]	Description	Comments
29	Incorrect calculation of open and wedged fields	Lack of an independent check of the treatment plan
30	Error in the wedge factor	Lack of effective procedures and documentation: lack of an independent check of the treatment plan Computer calculation was not manually checked
31	Wedge factors used twice in the calculation of the treatment time	Application without verification of a calculation adapted from another hospital Computer calculation was not checked manually
32	Failure to include intended wedges in the treatment set-up	No independent verification of the treatment parameters No inspection of the isodose distribution
33	Misunderstanding of the complex treatment plan given verbally	No written procedures for the treatment prescription Unclear verbal prescription Unusually complex plan involving two sites with different doses and different fractions
36	Calculation error after a change of treatment regimen	Lack of an independent check of the treatment plan Procedures were followed mechanically without sufficient awareness Ineffective weekly checking of the patient's chart
37	Confusion of fractional dose and total dose	Ineffective communication Three people failed to detect the error Unusual fractionation: failed to detect the error before the completion of the treatment
38	Incorrect positioning of treatment beams	Incorrect treatment set-up: poor implementation of instructions on the chart Patient set-up was not checked by another person: technologist worked alone
	Brachytherapy: Low dose rate sources and applicators	
53	Incorrect dose calculation owing to the use of the wrong source strength	Used units inconsistent with the manufacturer's source specification Insufficient training and/or understanding of the TPS software No independent check of computer calculations

TABLE 1. ACCIDENTAL EXPOSURES THAT RELATE TO THE RADIATION TREATMENT PROCESS AS SUMMARIZED IN REF. [4] (cont.)

Event[a]	Description	Comments
54	Inconsistent units of source activity	Incorrect data for the dose calculation, caused by the supplier Different units used by the manufacturer and physicist Consistency of sources ordered and received was not checked No source strength measurement at the hospital
55	Sources of incorrect activity	Incorrect data for the dose calculation, caused by the supplier Different units used by the supplier and hospital Consistency of sources ordered and received was not checked No source strength measurement at the hospital
58	Treatment time based on an incorrect isotope	Incorrect patient dose calculation (used ^{192}Ir instead of ^{137}Cs) No independent check of the treatment plan
59	Treatment planning based on the wrong isotope	Incorrect patient dose calculation (used ^{192}Ir instead of ^{125}I) Ineffective communication between the radiation oncologist and dosimetrist No independent check of the treatment plan
60	Error in the calculation of the dose from eye plaque	Incorrect patient dose calculation: eye plaque was altered without changing the dose calculation Dose calculation was not checked by a second person Procedure for calculation was not well defined
62	Error in the calculation of the time of removal	Incorrect dose calculation No independent check of the time of removal
63	Wrong treatment distance in the dose calculation	Incorrect calculation: the physicist used a form and a calculation method that were obsolete No independent check of the calculations
64	Treatment based on an obsolete treatment plan	Patient's treatment was based on a plan that was later revised Poor communication between the oncologist, dosimetrist and physicist

TABLE 1. ACCIDENTAL EXPOSURES THAT RELATE TO THE RADIATION TREATMENT PROCESS AS SUMMARIZED IN REF. [4] (cont.)

Event[a]	Description	Comments
65	Failure to implant all sources as planned	Oncology resident failed to carry out the treatment plan as prescribed Insufficient education Lack of effective procedures, protocols and documentation Ineffective communication

[a] Event numbers refer to the error number as recorded in Ref. [4].

by nearly 100% than the planned exposures, with the biologically equivalent doses being even greater than that.

The major issues that relate to treatment planning errors can be summarized by four key words:

(1) Education;
(2) Verification;
(3) Documentation;
(4) Communication.

1.4.1. Education

Education is required both at the technical and/or professional level in terms of the use of the TPS and at the organizational level with respect to institutional policies and procedures. A very important component of education relates to understanding the software capabilities and limitations. Especially relevant are issues that relate to dose calculation normalization procedures, treatment set-up parameters as used by the computer compared with the actual treatment machine, time or MU calculations, and inhomogeneity corrections. A misinterpretation of any of these calculation procedures can potentially lead to significant treatment errors. In brachytherapy, issues of significant concern relate to source activity specification and to how the algorithm uses this specification.

1.4.2. Verification

Nearly 60% of the reported errors involved a lack of an appropriate independent secondary check of the treatment plan or dose calculation.

1.4.3. Documentation

Clear documentation is required both of each patient's individual treatment plan and of departmental policies and procedures.

1.4.4. Communication

Communication among staff members is essential for all aspects of treatment, since various people at various professional levels are involved in the treatment process. Poor communication was a key factor in a number of the errors reported.

1.5. WHY IS QUALITY ASSURANCE REQUIRED?

QA is "all those planned and systematic actions necessary to provide adequate confidence that a product or process will satisfy given requirements for quality" [7]. Two considerations exist when addressing the need for QA: the first relates to the need for accuracy in the radiation therapy process, while the second relates to the avoidance of treatment errors.

1.5.1. Accuracy in the radiation treatment

It is well known that the biological effect of radiation on tumours and normal tissues behaves according to sigmoid shaped dose–response relationships. Clinical dose–response curves are recognized to be very steep, typically with a 5% change in dose resulting in a 10–30% change in response when looking at the steepest portion of such curves. A statement about the required accuracy in radiation treatment is based on the steepness of such dose–response relationships and on what accuracy is practically achievable when one accounts for the multiple steps involved in the radiation treatment process. On the basis of these considerations, the International Commission on Radiation Units and Measurements (ICRU) [8] recommended that the overall accuracy in the radiation dose delivered to the patient be 5%. A further analysis of uncertainties associated with radiation treatment shows that a 3% accuracy is required in the dose calculation to yield a 5% accuracy in the dose delivered to

the patient [8–10]. In practice, this recommendation means that it is the responsibility of the medical physicist to ensure that the TPS generates a dose calculation accuracy as close as possible to this 3% recommendation.

1.5.2. Avoidance of treatment errors

Errors in the radiation treatment process could lead to major changes in patient outcome, depending on the magnitude of the error. Examples of such errors are described in Section 1.4.

Thus the crux of QA for the TPS is to develop a process that ensures confidence that each patient will receive the optimal treatment as planned and that no errors will occur in the process of using the TPS or in the clinical implementation of the treatment plan.

1.6. BRIEF OVERVIEW OF THE CLINICAL IMPLEMENTATION OF A TREATMENT PLANNING SYSTEM

QA of TPSs is affected by the complicated process by which they are put into clinical practice. In brief, a TPS is developed by a commercial vendor, who codes input and output software, image display and manipulation software, the dose calculation algorithms, as well as the treatment plan evaluation tools. Even though the vendor may have clear descriptions of the algorithms, the user is not aware of the details of the coding of the algorithms, and therefore generally considers the system as a 'black box'.

In the context of this report, 'commissioning' means preparing the TPS for clinical use. In order to commission the TPS, appropriate parameters need to be entered by the user for the institution's machines, and measured data are required as input for the dose calculation algorithms. Thus the commissioning process involves a combination of entering measured data generated by the user and testing the TPS output using these measured data as well as the algorithms coded by the vendor.

Several issues need to be recognized in this process. Firstly, the software is complex and involves many components. Simple tests may thus test one pathway of use of the software but may not necessarily be representative of more general system usage. Secondly, with the rapid change in computer hardware and software, QA tests need to be repeated whenever software or hardware upgrades are carried out.

A generic QA process is more than just commissioning and quality control (QC). It begins with the purchase process of the TPS. The details of such a process will vary from one institution to another, and are dependent on

institutional size, available staff, computer expertise, other technologies in the department and financial resources.

1.7. TOTAL QUALITY MANAGEMENT

Total quality management (TQM) [11] is much broader in scope than dealing with the QA of individual procedures or technologies. It is an institutional focus that begins with upper level management and percolates throughout the entire organization. TQM includes developing clear organizational structures and reporting relationships. It also requires the instillation of an attitude of teamwork such that each individual recognizes the importance of his or her role as well as the roles of those around them. Intrinsic to TQM is process management, since often when problems occur it is the process that is faulty rather than individuals within the process. Thus ongoing process review and improvement is critical to TQM.

TQM and a good quality system in the context of radiation oncology provide a number of benefits [12]. To summarize, these include the following:

(a) A quality system ensures continuing quality improvement, especially since people and technologies may change.
(b) Introducing a quality system brings about a cultural change and involves people at all levels, not just at the management level. This provides ownership of the activity near the location of the activity [12].
(c) A quality system is a management tool that defines responsibilities unambiguously and provides thorough training and staff movements to different positions.
(d) A quality system raises the morale of staff, since they are all participants in the process and individual needs and training are recognized.
(e) A quality system increases efficiency, since targets are set that are realistic and reviewed on a regular basis.
(f) A quality system reduces the likelihood of accidents and errors.
(g) A quality system reduces the chance of litigation, because fewer errors occur.

1.8. PREVIOUS REPORTS

A number of published reports are available that relate directly to the commissioning and QA of TPSs [13–25]. In addition, various other reports deal

with more general aspects of QA in radiation therapy and may also include TPS considerations [8, 12, 26–31].

1.9. HOW TO USE THIS REPORT

This report is intended as a generic guide for the commissioning and QA of TPSs. This report, however, does not provide a simple or unique protocol for these tasks because:

(a) There is a wide variety of treatment machine capabilities, ranging from simple ^{60}Co machines, to complex treatment machines with MLCs, to intensity modulated radiation therapies (IMRTs);
(b) There is a wide variety of treatment procedures, depending on the institutional resources, patient imaging availability for treatment planning and treatment machine capabilities;
(c) Commercial TPSs have a wide variety of capabilities, ranging from relatively simple two dimensional (2-D) systems to comprehensive three dimensional (3-D) treatment planning capabilities that make full use of 3-D image data sets.

To provide guidance for this very large scope of capabilities, this report provides a comprehensive process that should be useful to every institution engaged in radiation therapy. However, in view of the large scope, this report is a compromise between being too detailed and exhaustive and being too brief and incomplete. Thus it has been attempted to provide guidance for the wide variety of treatment planning capabilities available. In order to demonstrate how this report can be used, in a number of sections are given examples of a subset of tests that need to be performed by a department having only basic radiation therapy capabilities, recognizing that every institution will need to decide what its specific capabilities are.

In addition to providing commissioning and QA guidelines, this report also has some sections that provide a contextual and educational perspective. This report is therefore divided into two major areas. The first eight sections provide background information that is useful and necessary in understanding the commissioning and QA activities outlined in the last five sections. This report begins with an introductory section (Section 1), which provides a brief background, a description of the target audience, an overview of TPSs and the need for their QA. Clinical treatment planning is described in Section 2. Section 3 reviews the basic components of a TPS. Section 4 addresses a number of issues and questions that need to be considered to gain insight into the

algorithms that are used by specific TPSs. Section 5 provides an overview of quality assessment and discusses uncertainties, tolerances and errors. Overall QA management, equipment and personnel requirements are described in Section 6. Sections 7 and 8 review purchase and acceptance considerations. Section 9 contains a detailed description of the commissioning of a TPS. While a comprehensive range of tests is described, this is supplemented with an example of the subset of tests that should be used for a department with only basic capabilities. As described in Section 9, the Appendix contains a table summarizing the tests, to give the user a broad perspective of what is to follow in that section, recognizing that not all of the tests will be performed by any one user but that the specific tests to be performed will depend on the specific TPS the user has. The Appendix can also be used as a checklist for commissioning a new TPS. Sections 10 and 11 describe periodic (ongoing) tests and patient specific QA, and Section 12 provides an overall summary.

Commissioning a TPS and developing a comprehensive QA programme for treatment planning is a significant undertaking in any department, no matter what the level of training of the staff or the available technology. Owing to the enormous variations throughout the world in infrastructure, resources, both human and physical, and available technology, this report does not provide a simple commissioning and QA protocol. Rather, it provides an overview of the factors to consider and provides guidance to every institution on how to implement and maintain a TPS in the clinical environment. It needs to be emphasized that a major component of commissioning a TPS involves educating the user on the system's capabilities and limitations. As indicated in Table 1, a significant number of treatment errors occur as a result of inadequate understanding of the operation of a TPS.

2. CLINICAL TREATMENT PLANNING PROCESS

2.1. RADIATION TREATMENT PLANNING PROCESS

The clinical radiation therapy process is complex and involves multiple steps, as shown in Fig. 1. The process begins with patient diagnosis, followed by a decision on whether to treat with radiation. This leads to a directive to move forward with the treatment planning process using a particular technique, protocol or set-up, which is then followed by a specific patient positioning or immobilization procedure. This component is very important, since all

treatment planning information must be obtained with the patient in the proper treatment position, such that the patient set-up can be easily reproduced from day to day. Errors or large uncertainties at this stage will be carried through the entire treatment process.

The shaded region of Fig. 1 highlights the stages of the radiation therapy process that specifically relate to treatment planning and represents the specific part of the process addressed in this report. This includes the derivation of anatomical information, which in its simplest form can be an external contour derived using some electrical–mechanical aid, or in a more sophisticated form will use data generated from some imaging procedure such as CT or MRI. At times, information from nuclear medicine procedures such as single photon emission computed tomography (SPECT) or PET may also be used for aiding the determination of target volumes. The use of ultrasound imaging is gaining prominence, especially for prostate brachytherapy.

As part of the imaging process, several reference marks should be placed on the patient. This can be done before imaging, using radio-opaque markers that will show on the images for beam reference positions during the planning process. Alternatively, this can also be done after the patient has completed the imaging process, possibly using the special laser system found with some CT simulators, to place reference marks on the skin surface. These skin marks are typically used to define a predetermined isocentre in the patient.

Once the appropriate external contour or image data have been obtained, the radiation oncologist will outline the target volumes and organs at risk. For contours generated with images other than CT, the contours are generally registered with the CT and then transposed on to the CT images, since it is the CT data that are usually used for appropriate dose calculations. Where there are no major tissue inhomogeneities, contour data from any source of imaging can be used directly for dose calculation, assuming the derived contours contain no distortions and that the tissue densities are equal to that of water. In some cases in which only external contours are measured, internal contours may be derived from films or other imaging sources and specific densities may be assigned based on published data.

With this information, the best beam arrangement will be determined to cover the target volume adequately while minimizing the dose to critical normal tissues. This will include a choice of beam directions and a choice of collimation (divergent blocks, asymmetric jaws and MLCs). A digitally reconstructed radiograph (DRR) can be generated to allow verification checks with portal images obtained during treatment. With this completed, a dose calculation is performed. The dose distribution is then evaluated using one or more of several possible procedures; for example, a simple review of the distribution itself will confirm whether the planning target volume is covered

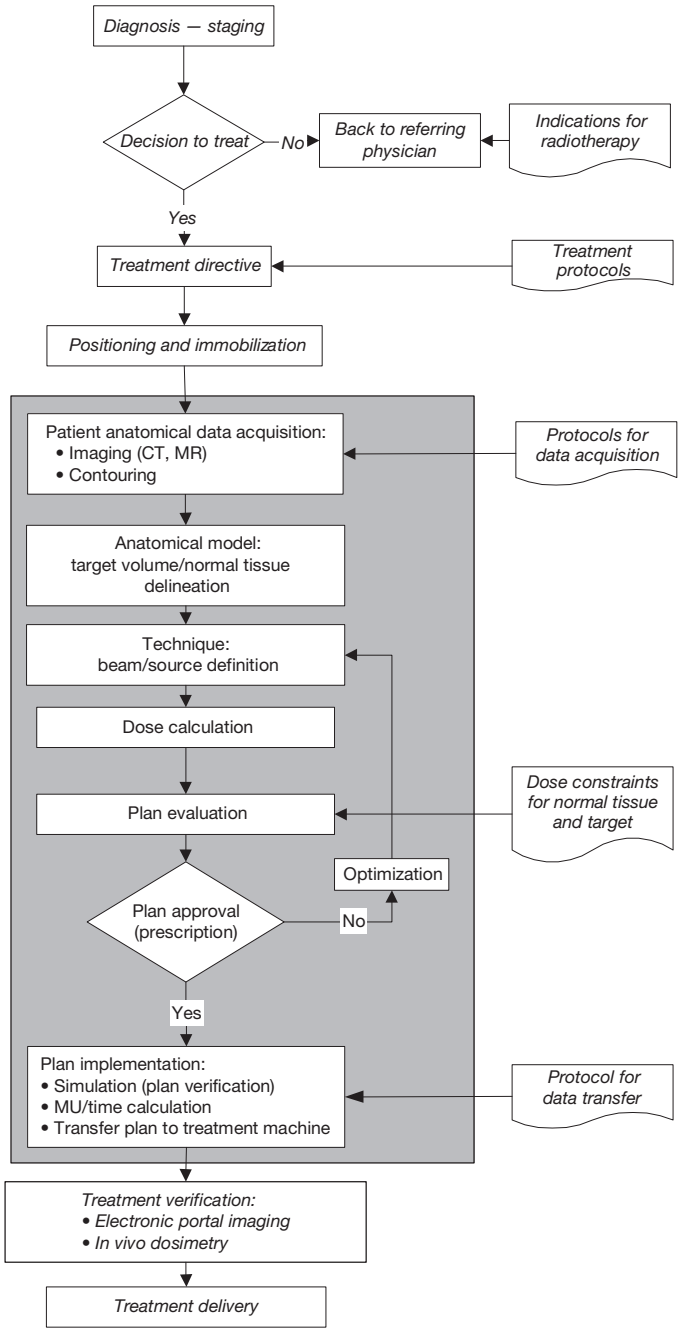

FIG. 1. Steps in the radiation therapy planning process. Note: Process parts in italics are not included in this report.

adequately and whether the normal tissues are being limited to acceptable doses. Alternatively, a plan evaluation tool could be used. One approach would be to use dose–volume histogram (DVH) analysis to assess the adequacy of the plan.

Finally, some TPSs will allow the use of a radiobiological model to estimate tumour control probabilities (TCPs) or normal tissue complication probabilities (NTCPs) to give an estimate of the quality of the plan. Such radiobiological calculations are still in their infancy and need to be used with caution, since their accuracy is questionable and even the assessment of trends is dependent on the particular model being used.

Depending on the equipment used in the department, a treatment plan may be confirmed by the use of a simulator and/or on the therapy machine by the use of a portal image (either electronic or film). For this comparison a DRR can be generated as a reference for assessing the adequacy of the set-up on the treatment or to compare directly with a simulator film. As part of the treatment preparatory process, ancillary devices may have to be constructed. Examples include casts, moulds, thermoplastic immobilization systems, compensators to compensate for surface contours or overall dose variations, and shielding blocks or other devices to aid the treatment.

2.2. CLINICAL IMPLEMENTATION OF A TREATMENT PLANNING SYSTEM

Ensuring treatment quality in radiation therapy embraces a recognition that the best equipment and techniques should be available for treatment planning. This includes the actual purchase and clinical implementation of a TPS. The general steps of implementing any radiation therapy technology into clinical practice include the following [32]:

(a) A clinical needs assessment;
(b) A selection and purchase process;
(c) Installation;
(d) Acceptance testing;
(e) Commissioning;
(f) Training;
(g) Clinical use;
(h) Periodic QA.

These steps are also relevant for the clinical implementation of a TPS and are described in more detail in subsequent sections of this report.

3. DESCRIPTION OF RADIATION TREATMENT PLANNING SYSTEMS

As indicated in Section 2, the TPS is at the heart of the radiation therapy planning process. A TPS comprises a computer, input and output devices, and software. Its main function is to enable the input of anatomical information for a particular patient, facilitate the selection of radiation beams appropriate to treat a designated target volume and produce a representation of the dose distribution that will be delivered within the patient. In addition, the TPS provides data that are subsequently used for treatment preparation and delivery.

The systems available commercially today offer a range of software features and hardware platforms, but the fundamental components of a TPS are common to all. The following sections briefly describe these components, for both basic and state of the art TPSs [25].

3.1. HARDWARE

The system will have one or more high speed central processing units (CPUs), with sufficient memory to run the software efficiently. It will have a graphics processor and monitor capable of rapidly displaying high resolution images. A large hard disk capacity is required for a considerable volume of patient data if image data are used. An auxiliary storage medium (disk or tape) is required for backup and for archiving data. A CD-ROM drive and a floppy disk drive are usual for loading new software and transferring data. A keyboard and mouse are standard. An electromagnetic digitizer is necessary for the manual input of patient contours and beam shapes. A text printer and colour plotter or combined printer–plotter is required for plan output.

There must be a device for transferring image data to the TPS. Usually this is a network interface card and local area network connection, although other devices, such as magnetic tape or a film scanner, can be used.

3.2. SOFTWARE

The TPS will be driven by the operating system software, usually proprietary products such as UNIX or Windows, with treatment planning software as an applications package. The planning software can be very complex, but can be considered to be a basic package with minimum require-

ments, with a range of additional features. Sometimes these additional features are standard, sometimes they are optional extras. The user needs to decide which of the additional features are relevant before purchasing and commissioning a system.

3.2.1. Three dimensional and two dimensional treatment planning systems

It is not always easy to characterize a TPS as 3-D or 2-D, as many systems include some but not all 3-D capabilities. However, a fully 3-D system will have:

(a) The option to reconstruct, from an image data set, views orthogonal and oblique to the original images.
(b) The ability to represent structures and dose distributions in a 3-D view, as well as a beam's eye view (BEV), of the anatomy.
(c) No restrictions on beam directions and orientations, other than those of the specific treatment unit. In particular, the system will support couch rotation.
(d) A dose calculation algorithm that takes into account 3-D patient anatomy, with respect to both the primary and scattered radiation.

Additional functionality in a 3-D system includes support for conformal beam shaping, DRRs and DVHs. Most 3-D TPSs now offer virtual simulation with DRRs.

For 2-D planning, only a limited number of contours on parallel slices need to be entered, and beam axes are parallel with these planes. Calculation algorithms assume that each of these contours is invariant over the length of the volume, and may not explicitly consider scattered radiation. Imaging requirements for such a system are minimal.

A 3-D system should also support simple 2-D planning, with manual entry of contours, as even in larger centres there is still a significant proportion of plans that do not warrant a 3-D approach.

3.2.2. Computed tomography simulation and three dimensional treatment planning systems

Several commercial systems are available that can be classified as virtual simulators [33]. In conjunction with a CT scanner, a virtual simulator can replace a treatment simulator. A virtual patient can be viewed in 2-D or 3-D, and beams can be positioned and shaped for a designated target volume. With sophisticated imaging software, and support for radiotherapy equipment, a

virtual simulator does much more than a simulator, since target contours, normal tissue contours and beam geometries can be viewed on any image type, such as transverse, coronal, sagittal, BEV and DRR images.

A virtual simulator also competes with the conventional use of a TPS, since it can do all of the front end of the treatment planning process. Some models can also display and analyse dose data. All that is lacking is the dose calculation algorithm itself, and even that is now available from at least one vendor of a CT simulator.

Over recent years there has been a progressive convergence of these two product lines. TPS vendors now offer a more complete range of imaging functions, and the quality of 3-D images and DRRs has improved so that state of the art TPSs can also be considered to be virtual simulators. The converse is also true: a CT simulator could be turned into a TPS by adding a dose calculation algorithm.

3.2.3. Input–output

Initially, beam data must be measured and transferred to the TPS. Software to interface some beam data acquisition systems with some TPSs is available. These programs format the data into the form required by the TPS and facilitate data transfer, usually by a removable media disk or a temporary link, although transfer via a network is also possible.

For treatment planning, tools for the transfer of image data are required. Series of CT slices are now most commonly received via a network in Digital Imaging and Communications in Medicine (DICOM) format [34], and must be converted to the TPS's internal format. Other methods of transfer, for example magnetic media, a film scanner or a network connection using non-standard formats, require interface software specific to that transfer. There must be software to interface the digitizer with the TPS, for the manual input of patient contours and shielding outlines. Hard copy output of a treatment plan is controlled by software that allows formatting choices such as scale, image or contour plot, device, etc., before handing control to system plot drivers. There should also be utilities to enable the backup, archiving and restoration of planning software and patient data to a mass storage device such as cartridge tape or a remote hard disk.

3.2.4. Contouring and image display

For image based planning there must be a contouring package that enables the interactive entry, editing and display of body contours (or at least the option to exclude parts of the image outside the patient), internal structures

(including target volumes), bolus and points of interest. This information then needs to be displayed graphically, either in conjunction with or without the original image set. This can be a 2-D representation, with the ability to select planes, or a 3-D model with volumes rendered from the contours. There will usually be options to rotate, pan, zoom and cut the views.

3.2.5. Beam input and calculation

There will be software to position and shape radiation beams interactively, facilitated by graphical representations such as a BEV and a room's eye view of the anatomy and beams. Beam modifiers (wedges, blocks and MLCs) can be selected and displayed. Other initialization parameters, such as the calculation grid, beam weights and choice of calculation algorithm, are set at this time.

At the core of the TPS is the dose calculation software, in which a beam model uses data directly measured for, or derived from, the user's beams; a calculation algorithm applies the data to a specific patient and plan geometry. This may take time, depending on the complexity of the algorithm. Some systems offer a choice of faster or more accurate calculations, others begin the calculation as a background process, so additional beams can be entered while the calculation is in progress.

3.2.6. Dose display

The calculated doses can be displayed by interpolating between the grid points to find isodose lines or isodose surfaces, which can be shown as different colours on 2-D or 3-D image displays. Interactive features allow the isodoses or displays to be chosen and edited, and beam weights and plan normalization can be altered as required. Other visual displays of the data include colour washes and dose profiles along a chosen line.

3.2.7. Plan evaluation tools

As well as inspection of the isodose display, other tools are usually available to assist in deciding whether a plan is satisfactory or to choose between alternative plans. This may be a side by side comparison on the screen, target volume dose statistics or simply the dose at chosen points of interest. Another tool is a cumulative DVH analysis, which enables a structure by structure comparison of plans and also shows whether a plan satisfies predetermined constraints. Some systems also offer biological models that calculate the TCP and NTCP, although these are not usually used in routine clinical practice

out of recognition that the models are still rather crude and limited in their estimations of biological response.

3.2.8. Other features

Other features offered include automatic external and internal multislice contouring tools, 'growth' of target volumes to include margins, registration of images from different modalities (CT, MRI and PET), beam compensators (including electronic compensation), automated routines for plan optimization and IMRT packages. There is ongoing competition to support the technology available on linear accelerators, such as dynamic or motorized wedges, different types of MLC and dynamic treatments.

3.3. SINGLE OR MULTISTATION SYSTEMS

When more than one workstation is purchased, it is usual to network them together, either directly or using the hospital's network. They can then share data storage devices and peripherals such as digitizers and plotters, although there are associated potential management problems. It is usual to configure a networked system so that all workstations can access all patient data, but each can perform dose computations locally. There may be physician viewing only stations or contouring only stations as part of the network.

3.4. ANCILLARY COMPONENTS

Sometimes a TPS may be linked to another device, such as a milling machine to fabricate compensating filters or a shielding block cutter. Generally the connection is via a network or a magnetic medium. The external equipment has its own software, and files are exported from the TPS. The files that drive linear accelerator MLCs are included in this category. Many TPSs now support the export of images and plan data to patient management and imaging systems. DICOM has been extended to include radiotherapy objects (DICOM-RT), and the emergence of this standard will greatly facilitate data exchange between these devices in a multivendor environment.

3.5. THIRD PARTY SOFTWARE

Some TPSs allow the computer to be used for additional (third party) software, provided it does not compromise the normal operation of the system. This could be an associated program developed in-house to process data from the TPS or it could be an entirely separate application that can make use of the computer's processing power. Examples include spreadsheet or database programs, Internet and email applications or departmental oncology management systems.

4. ALGORITHMS USED IN RADIATION TREATMENT PLANNING

4.1. INTRODUCTION

The functionality and quality of any TPS is dependent on the type of algorithms used in the different steps of the planning process. Generally speaking, an algorithm is the sequence of instructions that operates on a set of input data, transforming that information into a set of output results that are of interest to the user. A number of algorithms are used in the treatment planning process. The most well known algorithm is the dose calculation algorithm that generates the dose at any point within the patient while taking into account the patient and beam (or source) characteristics. However, many other algorithms are used within any TPS, especially the more advanced TPSs.

Knowledge at some level of the various algorithms used within the TPS can help the user understand the capabilities and limitations of the specific algorithms, can help the user diagnose TPS problems and can help with developing a QA process. A detailed description of all TPS related algorithms is beyond the scope of this report. In order to help users investigate the algorithms included in their TPSs, this section includes a number of questions that users may want to address. Answers to these questions may be obtained in part from:

(a) Scientific publications;
(b) Vendor documentation (including proper references or copies of the relevant publications);
(c) Specific training sessions (i.e. organized by the vendor);

(d) Participation in user meetings;
(e) Specific requests for information directed to the vendor;
(f) Contacts with colleagues using the same TPS;
(g) Qualitative tests performed by the user on his or her own system during commissioning.

By asking appropriate questions, the user can gain useful insights into the operation of the TPS. It is not expected that all users will need to address all the questions discussed in this section.

4.2. PROCESSING AND DISPLAY OF ANATOMICAL DATA

Depending on the method used for acquisition and transfer, the TPS anatomical data can be represented as a series of contours (both internal and external) or as a series of images (e.g. from CT). An important component of modern TPSs is the extraction of 3-D objects from these data, called structures, which are eventually used for plan preparation, dose calculation and plan evaluation. Examples of such structures are tumour and target volumes, inhomogeneities and organs at risk.

4.2.1. Contours and automated segmentation

When the anatomical information is available as a series of 2-D pixel matrices (or images), most TPSs provide an algorithm for automatic contour extraction. More advanced TPSs (or imaging systems) may make use of 3-D algorithms that can automatically contour (or segment) each individual structure from CT images (or the 3-D matrix of voxels that make up a set of images), as illustrated in Fig. 2. Some typical questions about contour generation are listed in Table 2. The questions listed change very little when one considers definition of 2-D contours from individual images, or segmentation of the entire 3-D surface of a structure from a 3-D series of images.

4.2.2. Building three dimensional objects (structures) from a series of contours

Since patients are three dimensional, treatment planning always involves representing the patient anatomy in 3-D in some fashion (even a 2-D TPS makes assumptions about what happens in the third dimension). Therefore, any TPS must generate a 3-D description of each structure of interest. Most TPSs construct the 3-D objects from a series of 2-D contours (typically

obtained with contours generated on each CT scan). In some cases, the image information is used to define the structures by identifying the voxels belonging to the structure (rather than contours). Construction of the 3-D structure description may require some kind of preprocessing. Whichever algorithm is used, various difficulties may be caused by irregular slice acquisition, details of the contour generation or other problems.

There are three major ways to represent such a 3-D structure for treatment planning, as illustrated in Fig. 3. The object may be defined by a surface description (Fig. 3(a)), in which the surface is created from a series of rectangular or triangular tiles that connect the various contours. A second description is volumetric (Fig. 3(b)), in which individual 3-D voxels are combined to create the structure. Finally, the structure can also be represented by a series of individual points (which may be placed randomly or on a grid)

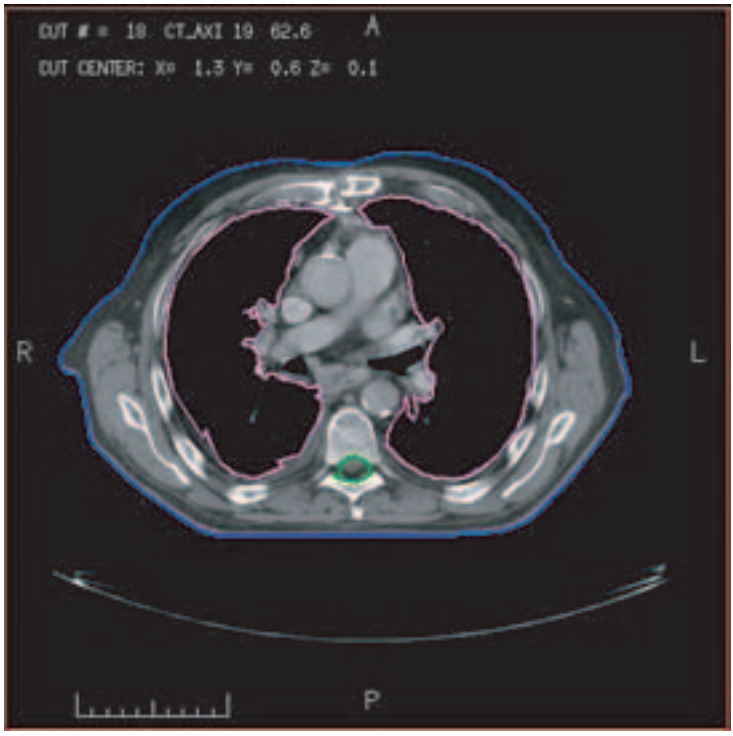

FIG. 2. CT scan with automatically segmented contours. Contours (the lungs and spinal cord are shown) can be generated by automatically extracting contours for objects that have different densities than the surrounding tissues (e.g. lung or bone).

TABLE 2. AUTOMATIC EXTRACTION OF CONTOURS OR SURFACES

Broad question	Specific question
What is the principle of contour (2-D) or surface (3-D) extraction?	Grey level threshold or gradient tracking? More sophisticated segmentation algorithm?
How is the extraction process initiated?	Starting point 'seed'? (Manual or automatic?) Density value? (Manual or automatic?)
Is there any special postprocessing of contours?	Is this processing automatic, systematic or under the user's control? Does it reduce the number of contour points? Is there curve smoothing?

(Fig. 3(c)). Often, the TPS will use more than one of these representations for a particular structure at different points in the planning process. Understanding the type of representation, and the limitations implied by that representation, may therefore help the user handle many of the QA issues associated with the anatomical description of the patient.

When contours defining the structure are drawn on sequential CT slices, at the top and bottom of the structure, there is a slice on which a contour is drawn, and then the next slice on which no contour is defined. How the TPS completes or caps the structure is an important aspect of planning. A number of methods are typically used, including: (a) just stopping the structure at the last slice's contour; (b) a simple extension of the last contour (perhaps half the distance to the next slice); and (c) capping the structure with a conical cap that extends a certain distance from the last slice. This decision often turns out to be important for the definition of the superior and inferior borders of the target

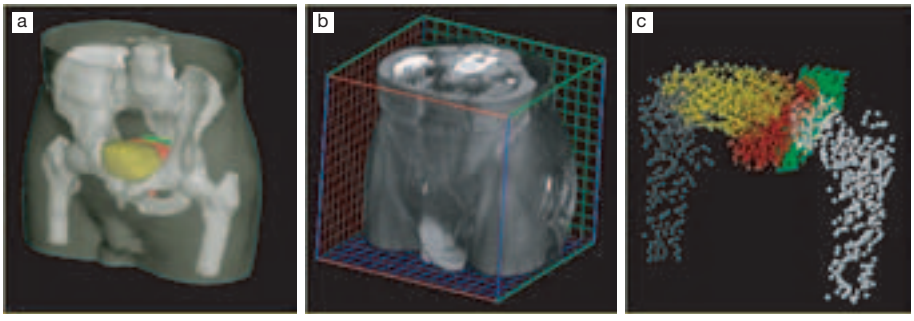

FIG. 3. Representations of 3-D anatomical structures: (a) surfaces, (b) voxel based description and (c) structures defined by random points.

volume, particularly when BEV display and aperture creation are used to define the treatment fields.

For density corrections, the definition of special structures to be treated as inhomogeneities is important. For non-CT based planning, these 3-D structures are defined from 2-D contours, and then assigned a density. For CT based planning, the density is usually obtained by conversion of the CT numbers into relative electron densities. The method of conversion and averaging should be described, as well as the resolution and form of the density information. Some TPSs use separate density grids, while others use the input CT data directly.

Table 3 gives some examples of questions that could be asked in order to obtain a better understanding of the method used to build and display anatomical 3-D objects.

4.2.3. Multiplanar reconstruction and three dimensional display

In a number of circumstances, anatomical information has to be displayed in different planes or as a 3-D representation, as illustrated in Fig. 4. To create any of these displays, various algorithms process the contours and images to generate the information to be displayed. These algorithms may be developed specifically for the TPS application, while others use very general third party graphical software packages. Table 4 gives some examples of questions that could be asked to enable a better understanding of such methods of reconstruction and display.

4.2.4. Expanding three dimensional objects (structures)

Modern treatment planning is often based on the definition of the gross tumour volume (GTV), clinical target volume (CTV) and planning target

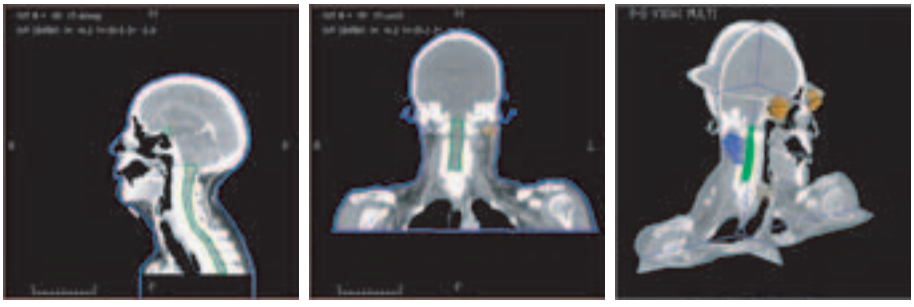

FIG. 4. Displays of sagittal, coronal and multiplanar CT information.

TABLE 3. BUILDING AND DISPLAYING 3-D OBJECTS

	Question
Objects defined from contours	Are the objects built as a 2-D contour stack, a 3-D surface, a 3-D voxel representation or a series of points? What happens when scans do not cover enough area of the patient? What is the shape of the structure above the last contour (capping)? What happens when only a limited number of contours (down to only one slice) are available?
Objects defined from a series of images	Is there any preprocessing of the image data in individual slices? How is the volumetric matrix built from individual slices? What happens when the images are not obtained at uniform spacing?
Data used for inhomogeneity corrections	How is the conversion of CT numbers to electron density performed? Is there an independent density representation? Is the voxel size different for the anatomical and density representation? Is there any density averaging between adjacent voxels?

TABLE 4. MULTIPLANAR RECONSTRUCTION AND 3-D DISPLAY

	Question
2-D image representation	Is there any interpolation, smoothing or filtering of pixels?
Display of 3-D objects on 2-D planes	In the display, is the 3-D representation of the plane of the image defined by the external surface of the object? Are the objects to be displayed on the plane obtained from the intersection of the object surface with the plane or from the voxel representation of the object?
3-D volume and surface display	Are 3-D representations based on images, contours or both? What is the tile geometry used for surface rendering? How are the lines defined in wire frame representations?

volume (PTV), as described in Ref. [35]. While the GTV (and often the CTV) is typically based on contours drawn on CT images by the physician, often the PTV is defined by creating an expansion around the CTV using a given

TABLE 5. EXPANDING OBJECTS

General question	Specific question
What is the general method for expansion?	2-D? 3-D? Does the shape of the structure on one slice affect how the expansion is created on other slices? Is it possible to exclude other structures from the expansion process? How?
What happens when not enough CT scan data are available around the initial object?	How does the number, thickness and spacing of adjacent slices influence the expansion process?
What is the resulting object after expansion of:	A cube? A sphere?
Requirements for margins?	Minimum value (= spatial resolution)? Relationship between this minimum and slice thickness? Possibility of asymmetric margin? Possibility of negative margin? (How is it applied on the upper and lower slice?)

(isotropic or anisotropic) margin. The method used for this expansion varies from TPS to TPS, and can also work on a slice by slice (2-D) basis or in a full 3-D manner, as illustrated in Fig. 5. This type of algorithm can also be used for hollow organ structures (like the rectum) to generate a wall of a given thickness or to generate bolus on top of the external patient surface. An incorrect understanding of the capabilities and limitations of such algorithms could result in severe errors in the definition of the volumes. Examples of relevant questions that could help to avoid such errors are listed in Table 5.

4.2.5. Creating digital reconstructed radiographs

DRRs (Fig. 6) are generally obtained by ray tracing through the volume of CT data from the (point) radiation source to the plane used for the DRR image. For each pixel on the image plane (perpendicular to the beam's central ray and defined at a given source to film distance), the ray tracing from the source to the pixel adds up the attenuation calculated for the voxels along the ray, and the total attenuation is used to create the grey level of the DRR (virtual film). The mathematical solutions for volume reconstruction, representation, ray tracing, density sampling and calculation of the overall attenuation

TABLE 6. DIGITALLY RECONSTRUCTED RADIOGRAPHS

	Question
Image quality	How is the resolution of the DRR determined? How is the display contrast set? Is there any tissue (density range) selection? Is it dependent on beam orientation? Can the energy of the DRR be changed (made like a diagnostic or megavoltage image)? Can a depth range for image reconstruction be selected? Is the image quality (noise and resolution) affected by the sampling method?
Display	Is it possible to overlay the projection of structures? How are the structures and/or contours displayed?

are also subject to many variations. Answers to questions such as those listed in Table 6 should help to give a better understanding of the underlying algorithm.

4.2.6. Registration of multiple anatomical data sets

When the CT images do not provide a satisfactory delimitation of the structures, it is often very useful to complement the anatomical CT data with

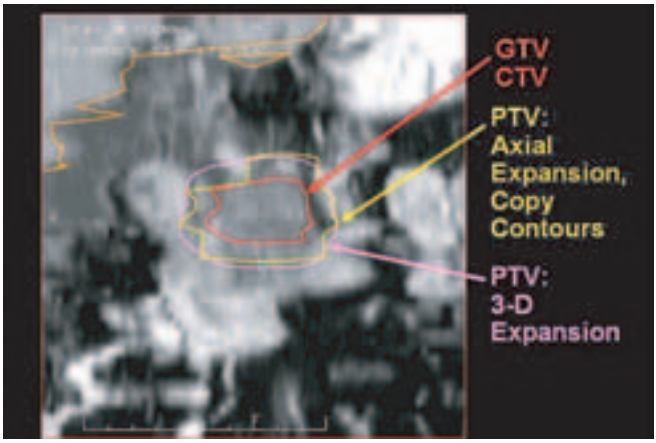

FIG. 5. Comparison of target volume (PTV) expansion methods on a coronal CT reconstruction of the pancreas. The light line shows 2-D expansion by expanding contours in 2-D and copying contours at the upper and lower ends of the target. The light grey line shows a fully 3-D expansion of the PTV.

data from another imaging modality (MRI, PET, ultrasound, etc.). It is then necessary to register the two different data sets (by aligning the co-ordinates or defining the co-ordinate transformation between the data sets), as in Fig. 7 [36]. Since there are generally some differences in patient position, tissues imaged or basic scan geometry between the two data sets, the TPS software can include specific tools for the registration. Some characteristics of the registration algorithms can be better understood from answers to questions such as those listed in Table 7.

4.3. BEAM OR SOURCE RELATED TOOLS

Various algorithms are used for defining beams, sources or other characteristics needed for the description of the plan.

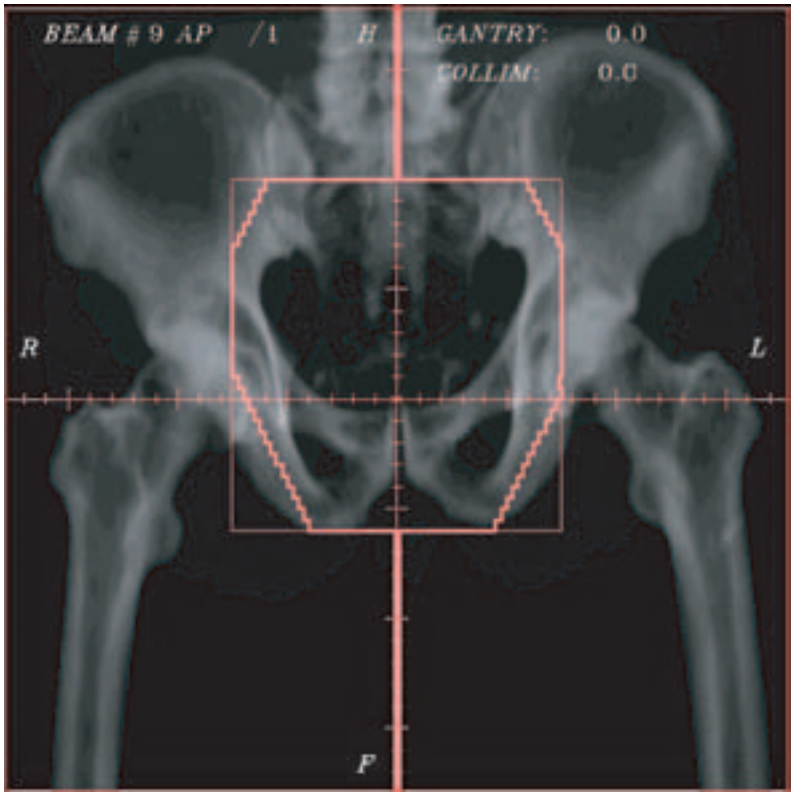

FIG. 6. Example DRR with BEV display of the beam's MLC aperture overlaid on top of the computed image.

4.3.1. Automatic design of beam apertures

The shape of the beam defining aperture (collimators, blocks and MLCs) is sometimes drawn manually, but often it is calculated automatically by adding a margin around a target structure as seen from the source in a display. Since this algorithm determines the shape of the beam, and how it will cover the target volume, it is crucial to understand the questions listed in Table 8.

4.3.2. Geometrical reconstruction of sources in brachytherapy

The main methods for geometrical reconstructions of sources in brachytherapy are listed in Table 9, which includes some examples of questions useful for the clarification of algorithms.

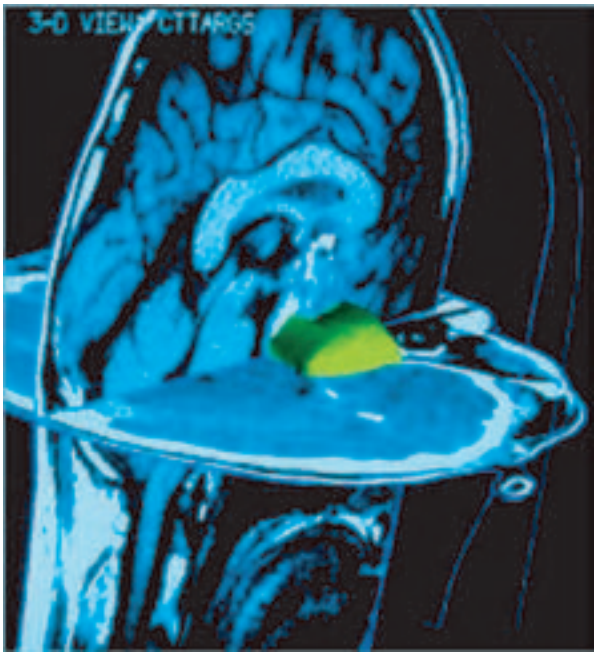

FIG. 7. Registered CT (axial slice) and MR (sagittal image), along with the CT defined target volume (yellow). For more details see Ref. [36].

TABLE 7. REGISTRATION OF MULTIPLE ANATOMICAL DATA SETS

	Question
Types of anatomical data set	Which imaging modalities are supported? Is one modality assumed to be the reference? Are there any specific requirements for image acquisition?
What is the general principle used for registration?	2-D or 3-D? Manual or automatic? Are there only rigid transformations or is distortion allowed? Are translations and/or rotations allowed? Is there a unique algorithm for images and structures? Is registration based on markers, surface matching, volume matching or image content?
How is the accuracy confirmed?	Is there an index or is a visual check used?
How are the data from multiple data sets used?	Display side by side (with or without cursor synchronization)? Display with overlay? Image fusion?

4.4. DOSE CALCULATION IN EXTERNAL BEAM RADIOTHERAPY

4.4.1. Dose calculation problem in external beam radiotherapy

Many different types of dose calculation algorithm are used in modern TPSs [25, 37, 38]. Early TPS calculation models were based on a simple tabular representation of the dose distribution that was obtained directly from beam measurements. Over the years, as calculation models have become more sophisticated and computer power has grown, TPS calculation algorithms have progressively evolved towards more physically based models. The most advanced current algorithms now are based on the Monte Carlo approach, in which the histories of many millions of photons are traced as they interact with matter using basic physics interactions. There is a full range of possibilities between table based models and Monte Carlo models. For every algorithm, the quality of the dose representation is strongly dependent on the data or parameters used by the algorithm.

The nature and quantity of the data required varies according to the model. Typically, for measurement based models a lot of tables are required, whereas for physical based models only some parameters might be necessary.

TABLE 8. AUTOMATIC DESIGN OF BEAM APERTURES

	Question
General	What is the general principle for the calculation of the shape?
	What would be the resulting shape for a square (or circular) PTV seen in BEV?
	What is the spatial resolution (i.e. for margin definition)?
	Is it possible to exclude organs at risk or to combine structures?
Blocks	How are the blocks defined (individual polygons or a single continuous line)?
	How is the field shape converted into blocks?
	Are there any recalculations, adjustments or limits concerned with the settings of the main jaws?
	For individual blocks, how is the closing line (under the main jaws) determined?
MLCs	How is the leaf tip adjusted on the field outline: midpoint, external, internal or all?
	How are the upper and lower leaf sides adjusted on the field outline?
	Is there any algorithm for collimator rotation optimization? How does it work?
	Are there checks to reject and/or correct unacceptable leaf patterns?
	Are there any recalculations, adjustments or limits concerned with the settings of the main jaws?

It is important for the user to understand: (a) the general principles of the model; (b) the implementation details; and (c) that model parameters and input data may all have a significant impact on the accuracy of the calculation results. Each model suffers from limitations, which may lead to the risk of misinterpreting some of the calculation results; for example, if a model is unable to deal with inhomogeneity corrections, it is necessary to recognize that fact, and if the issue is considered to be important a manual correction for the inhomogeneities must be used. On the other hand, an inhomogeneity correction might be part of the model and give acceptable results in a number of circumstances but deviate significantly in other situations. Finally, even if the model is able to account for a given physical effect, the actual implementation in the treatment planning software is often simplified, leading to inaccurate or unexpected results for certain situations.

The dose calculation of the TPS should predict the dose at any point in the patient, for each single fraction and for the overall treatment. Since the dose is built from the contribution of each beam in the plan and since the

TABLE 9. GEOMETRICAL RECONSTRUCTION OF SOURCES FOR BRACHYTHERAPY

	Question
Stereo-shift or multiple view (i.e. orthogonal) methods	How many views (X ray target locations) can be used?
	What are the constraints for the positions of the X ray target and film?
	Is there any requirement for fiducial markers? What are they used for?
	What are the basic geometrical data used for reconstruction?
	Is there any assumption for average source location (or average magnification factor)?
	Is there any algorithm for automatic source recognition on (digital) images? How does it work?
	Is there any algorithm for source identification on multiple views? How does it work?
	Is there any calculated correlation index to assess the validity of the reconstruction?
	For curved wires, is it necessary to identify the same segments on the different views?
Reconstruction from a series of parallel slices	Is there any algorithm for automatic source recognition on individual slices? How does it work?
	Are there any constraints for slice characteristics (i.e. thickness or position)?
	Is there any interpolation of source position between slices?
	Is there any algorithm for automatic source identification on the slices? How does it work?
	Is there any check or complementary information to assess the validity of the reconstruction?

contribution from each beam is the result of assigning a given treatment time or number of MUs, all parts of the calculation should be performed accurately. For practical reasons, dose calculations, as well as dose measurements, are often split up into two main components:

(a) An absolute dose component (expressed in Gy/min or Gy/MU), which usually makes use of a reference point chosen for each beam, together with some reference conditions;
(b) A relative dose component (expressed in per cent), based on normalizing the full dose distribution and linked to the absolute contributions of the beams.

Most efforts in the past have concentrated on the accuracy of the computation of the relative dose distribution, without always clearly recognizing the necessary link with the absolute dose component. Below, we first discuss algorithms for relative dose calculations, followed by the problem of absolute dose and MU/time calculations.

4.4.2. Relative dose distribution

To simplify the discussion of the various algorithms, a general classification of types of algorithm is listed in Table 10. These basic classes of algorithm are important to understand, because each type of algorithm requires different amounts of data and different types of commissioning and QA check, and is susceptible to different types of problem and error.

TPS users are strongly encouraged to find out about their calculation algorithms and to read enough documentation that they understand what is actually implemented in their system.

The classification in Table 10, which is independent of geometrical issues such as dimensionality, is somewhat arbitrary. Another way to differentiate between algorithms is based on their ability to consider 1-D, 2-D or 3-D geometry in the calculations. Note that the terms 2-D and 3-D are often used in misleading ways, since there are many different parts of the dose calculation process that depend on geometry. It is clear that most modern TPSs handle non-coplanar beam arrangements and give the dose at any point in the patient (i.e. in 3-D). However, this does not necessarily mean that the dose modelling considers all the 3-D geometry of the patient and beam.

Figure 8 illustrates one way to differentiate between 1-D, 2-D and 3-D dose computation modelling for the effects of surface curvature, inhomogeneities and missing tissues. In Fig. 8(a) (1-D), the only issues that are included in the dose calculation are those taking place on the line joining the source and the point of interest P, ignoring the shape and composition of tissues in the rest of the medium. In Fig. 8(b) (2-D), the patient is assumed to be cylindrical and the only corrections accounted for are those in the axial cross-section passing through point P. In Fig. 8(c) (3-D), the shape and composition of the patient are considered fully in 3-D. This is only one of many ways to consider the problem, and is not unique, since a combination of these possibilities is often encountered (i.e. ignoring missing tissues but accounting for lateral inhomogeneities, etc.). It must also be emphasized that a 3-D model does not provide a guarantee of the validity of dose computation. In many clinical situations a ‘good’ 1-D algorithm that, for example, accounts for the scatter contribution assuming a flat surface above the point of interest is quite satisfactory. There are, however, a number of circumstances in which the quality of the results is

TABLE 10. TYPES OF EXTERNAL BEAM CALCULATION ALGORITHM

	Data required	References
Based on measured data	Large amounts of measured data are entered directly into the TPS and reproduced by the algorithm; depth dose profile data may be entered directly into the TPS	[39]
Analytical functions	Analytical functions model the physics, but the parameters for the functions are usually fitted using measured data	[40]; normalized fractional dose [41]
	The tissue air ratio–scatter air ratio (TAR–SAR) separation of primary and scatter components could be considered, as well as a superposition of differential elements	TAR–SAR [42]
Superposition of differential elements	Algorithm integrates over differential dose elements; spectral data and some representation of the photon fluence are required, but limited other parameters are needed	Photons: convolution and superposition [43–45]; electron pencil beams [46]
Monte Carlo based models	Virtually all input data are the basic physics of interactions, and include very little measured data; however, most Monte Carlo methods involve modelling of the machine collimation system and radiation sources, etc.	[47, 48]

strongly dependent on the type of algorithm implemented; this is especially relevant if there are stringent requirements in terms of accuracy.

Tables 11–14 are given as examples and should provide some guidance to TPS users by listing some of the issues that may help the user understand the possibilities and limitations of a given algorithm implementation.

4.4.3. Monitor unit/time calculations and plan normalization

Since the final goal is to know the absolute dose distribution, it is important to understand precisely the relationship between the MUs (or treatment time) and the calculated dose distribution. Some TPSs allow a direct calculation of the MU (or treatment time) as part of the TPS dose calculation

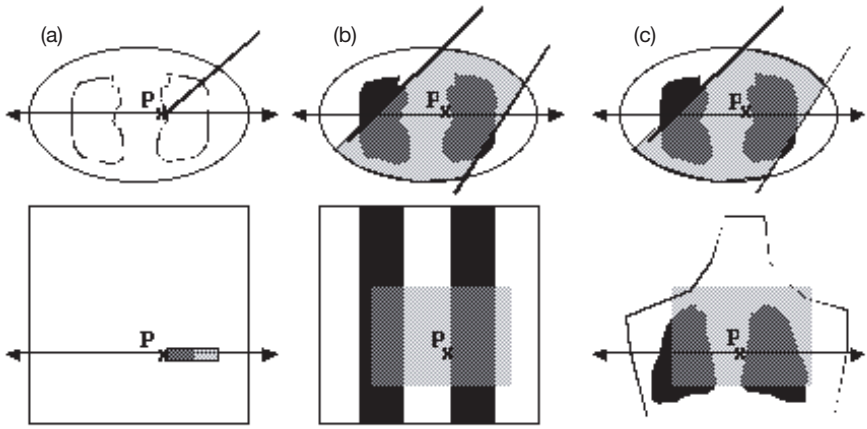

FIG. 8. Types of scatter correction. Illustration of one example of differentiation between (a) 1-D, (b) 2-D and (c) 3-D dose calculation at point P. The upper and lower parts of the figure represent the axial and coronal section through point P, respectively. The grey shaded area is the anatomical region (curvature, inhomogeneities, missing tissues) that is taken into account for dose computation.

algorithm, while others provide separate modules for MU calculations. In addition, the dose distribution can be expressed as absolute dose or as a percentage of the dose at some normalizing point. In all circumstances, the crucial issue is a clear understanding of the beam normalization (or weighting) mechanism, since this can significantly differ between various TPSs or even between different techniques used on the same TPS. This is further discussed in Section 9.4.6. Some questions to help define some of the issues are listed in Table 15.

4.4.4. Other issues in dose calculation for external beam radiotherapy

In spite of the large number of questions listed in the above mentioned tables, they do not cover all possibilities. One reason is that each dose calculation algorithm has its own characteristics and options; another is that there are other features, directly or indirectly linked to dose calculations, that are generally available.

While graphical display of the dose distribution is useful, DVHs can also help the user assess the quality of a treatment plan. DVHs are based on the dose calculation in a large number of points, each of which is representative of an elementary volume of tissue, spread out over the various structures of interest (target volumes and organs at risk). Various DVH algorithms differ in

TABLE 11. EXTERNAL BEAM DOSE CALCULATION ALGORITHM: DOSE IN WATER-LIKE MEDIUM WITHOUT A BEAM MODIFIER

	Question
General principle of relative dose calculation	From interpolation in tables? From analytical functions? By addition of primary and scatter components? By superposition of pencil beam kernels? By superposition of point dose kernels? By Monte Carlo calculation? From a combination of the above possibilities?
If an integration (or superposition or convolution) algorithm takes place	What are the shape and dimensions of the volume elements? What are the limits of the integration volume? Is it applied differently for each of the dose components (i.e. primary, scatter, etc.)? Is there any correction for spectral modifications with depth?
Influence of flattening filter	Is there a correction for intensity and quality variation across the beam (horns)? Is there a correction for scatter radiation from the head and flattening filter (extrafocal)?
Influence of main collimator (photons) and/or applicator (electrons)	What is the model used to describe the profile in the penumbra region? How is it adjusted to match the actual measurements? Is there a difference between the *x* and *y* collimator pairs?
Dose in the buildup region	Is there any specific model to describe the dose in the buildup region? Is it sensitive to patient surface obliquity? How? Is it sensitive to beam modifiers, including block trays? How?

the methods used to select points, distribute them into structures and bin the dose values. Two main methods exist for point selection: the systematic covering of the structures with a 3-D grid (or a series of 2-D grids), or points randomly chosen throughout each structure. The important point is to make sure that the point density and distribution are representative of the full dose distribution. In some cases, simplifications are used to speed up the DVH calculation. These should be recognized and judged whether to be acceptable. By way of an example, Fig. 9 demonstrates four different DVH displays for the same dose distribution.

Beyond dose calculation, some TPSs now attempt to model the biological effects of the delivered dose. These effects may include provision for dose fractionation corrections (i.e. considering the difference of dose per fraction at

TABLE 12. EXTERNAL BEAM DOSE CALCULATION ALGORITHM: INFLUENCE OF BEAM MODIFIERS

	Question
Wedges (photons)	Is there provision for physical wedges? Is there provision for dynamic (virtual) wedges? Is there provision for integrated wedges ('flying', built-in moving wedges)? If yes, are they treated in similar ways? How is the relative wedge transmission (intensity) calculated? Is it used to adjust: The total dose? The primary component only? The primary and scatter component separately? Is there any correction for spectral modifications? On the beam axis? In the wedged direction? In the non-wedged direction? Is there any correction for scatter and/or electron contamination from the wedge filter?
Attenuators and compensators	Is there provision for the insertion of attenuators or compensators? If yes, similar questions as for wedges Can variable attenuator thicknesses be used across the beam in 1-D or 2-D? Can compensator thicknesses be determined from the dose calculation? How?
Shielding blocks (photons and electrons) and inserts (electrons)	Is there a difference between the penumbra from the main collimator and from the block? Is there a different model for individual blocks and cut outs? How is the relative block transmission taken into account? Is it related to the primary component alone or to the total dose? Is the reduction of the patient scatter (compared with open field) accounted for? How is the block penumbra taken into account? Is there any provision for non-divergent shielding blocks? Is any modification of the head scatter component taken into account?
Tray	Is the contamination of the shielding trays accounted for?

each point) or the computation of global indices such as the TCP [49] and NTCP [50–52]. Before any of these biological models are used, a careful study of the algorithm and its predictions must take place, and the relevance of the predictions with respect to clinical data must be understood.

When the TPS supports the use of compensators, the user should investigate the method used for dose calculation with the compensator, and the method used for the compensator design. A full description of the

methodology, from the prescription of the compensation to the construction and check of the compensator, should be available to the user. The method used for computation of the number of MUs is of particular importance.

The same considerations hold for IMRT, in which an inverse planning algorithm replaces the interactive definition of the beam characteristics and automatically calculates the optimal beam modulation in order to satisfy a number of predefined criteria related to the dose distribution in the target volumes and organs at risk. Such algorithms are quite complex and sensitive to many parameters. They are often viewed by the user as 'black boxes' to be used

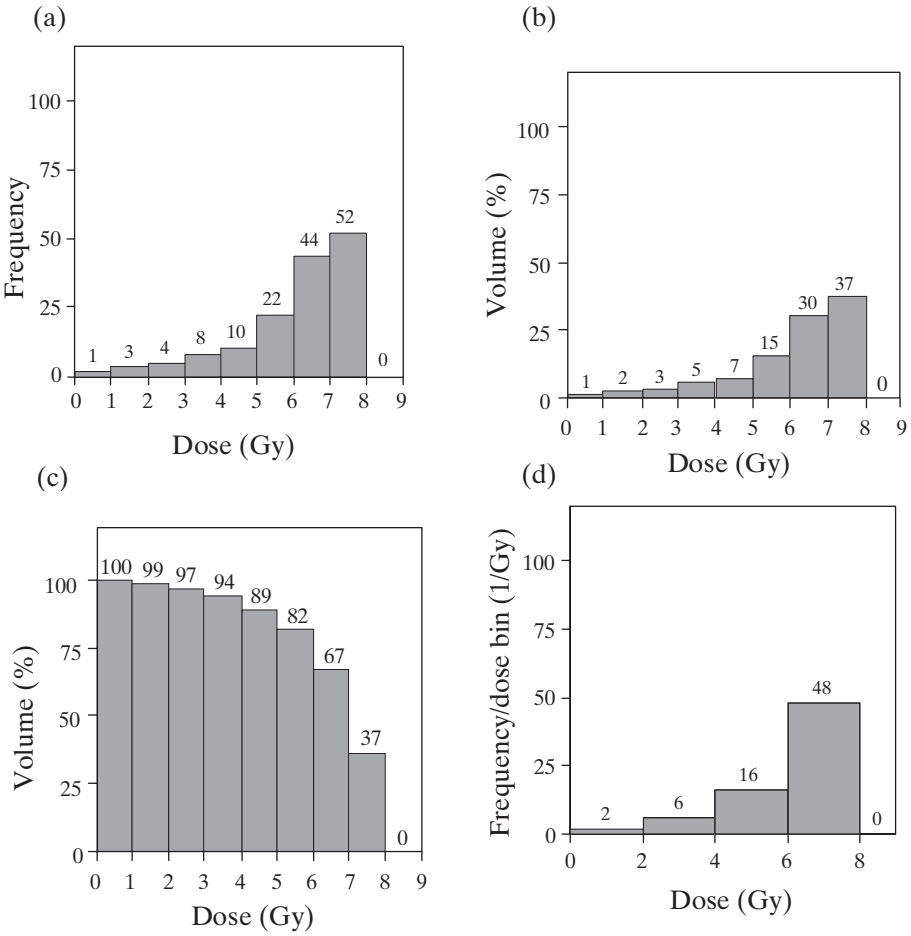

FIG. 9. Four different DVH displays for the same dose distribution and structure. (a) Direct DVH (number of voxels versus dose). (b) Direct DVH (per cent volume of structures). (c) Cumulative DVH. (d) Differential DVH (frequency/dose bin).

TABLE 13. EXTERNAL BEAM DOSE CALCULATION ALGORITHMS: SPECIAL COLLIMATING SYSTEMS

	Question
Asymmetric fields	Is the actual field shape as delimited by individual jaws accounted for?
	Is the dose calculation algorithm similar to the field delimited by blocks?
	Is there any special processing for the penumbra region?
MLCs	Is the actual field shape as delimited by individual leaves accounted for?
	Is the dose calculation algorithm similar to the field delimited by blocks?
	Is there any special processing for the penumbra region at the leaf tip and edge?
	Is there any provision for leaf transmission?
	Is the additional attenuation through the main collimator (if applicable) also considered?
	Is there provision for interleaf leakage?

following guidance from the vendor or other experienced users. One very important point is the validity of the resulting dose distribution, which should account for the detailed characteristics of the collimating system (penumbra, transmission and leakage) and be valid even for the small apertures often used in IMRT. Computation of MUs is of crucial importance. For further discussion of IMRT, the user can refer to Ref. [53].

4.5. DOSE CALCULATION IN BRACHYTHERAPY

4.5.1. Dose calculation problem in brachytherapy

The algorithms used for dose calculations for brachytherapy are generally much simpler than those for external radiotherapy. Since the geometrical dispersion of photons (the inverse square law for a point source) is the predominant cause of the shape of the dose distribution, the patient shape and inhomogeneities are generally ignored and the brachytherapy sources are assumed to be located in an infinite water medium. Part of the calculation deals with geometrical considerations and consists of a co-ordinate transformation

TABLE 14. EXTERNAL BEAM DOSE CALCULATION ALGORITHM: INFLUENCE OF PATIENT INHOMOGENEITIES AND MISSING TISSUES

	Question
General characteristics	Is there provision for inhomogeneity corrections? Are the inhomogeneities described as contours or as a matrix of voxels? Is the density value obtained from CT numbers through a customizable calibration curve? Is the atomic composition of tissues used for dose calculation? Is the influence of inhomogeneities included directly in the dose calculation? Is the influence of inhomogeneities treated as a correction factor in the dose computed to a water-like medium?
Modification of scattered photons	Is scatter accounted for in the case of inhomogeneities located: Above the point of calculation? Under the point of calculation? Lateral to the point of calculation (in-plane)? Lateral to the point of calculation (off-plane)? Are all scattering orders (first, second,…, multiple scatter) considered?
Modification of electron transport	Is it accounted for in the case of inhomogeneities located: Above the point of calculation? Under the point of calculation? Lateral to the point of calculation (in-plane)? Lateral to the point of calculation (off-plane)?
For electron beams	Are changes in the electron range accounted for? Are changes in the scattering angle accounted for?
Missing tissues (compared to a semi-infinite medium below a flat surface through the entrance point)	Is the difference between a flat surface and the patient's actual surface accounted for? Not at all? In a single slice? Or assuming a cylindrical patient, in a full irradiated volume? If part of the field is outside the patient's limits (i.e. in air), is it accounted for? Not at all? In a single slice? Or assuming a cylindrical patient, in a full patient volume? Is the lack of backscatter accounted for? By which method?

from a co-ordinate system linked to the source to a system linked to the patient (i.e. points belonging to calculation points).

The most critical issues in brachytherapy dose calculations are:

(a) A consistent choice of the mode of specification of the source strength and the use of relevant units;

TABLE 15. DOSE NORMALIZATION AND ABSOLUTE DOSE CALCULATIONS

	Question
Reference point for beam dose normalization (beam weighting)	Is it possible to define such a point independently from the reference point for the beam position?
	How is the associated SSD calculated? Including double obliquity for points that are both off-axis and off-plane? Including bolus thickness?
	How is the associated depth defined (i.e. SSD technique) or calculated (i.e. isocentre)? Including inhomogeneities? Including bolus? Does it account for the presence of air for complex surfaces (i.e. through the ear, etc.)?
	If it is relative to the entrance dose (at d_{max}), how is this d_{max} depth calculated? Is it extracted from lookup tables? Is it based on the same algorithm as for relative dose calculation?
	If the normalizing depth is searched by systematic on-axis dose calculation: What is the depth resolution? Does it include the effect of beam modifiers? Does it account for the actual field size and/or shape? Does it account for the presence of inhomogeneities?
Value for beam dose normalization (weight)	How is this value related to the total dose or dose and/or fraction for the actual beam?
	How does the relation between weight and dose depend on: Patient characteristics (shape, inhomogeneities, etc.)? Beam modifiers and beam limiting devices?
	Does it allow for the direct calculation of the treatment time (or MUs)?
Calculation of the treatment time (or MUs)	How is it linked to the measured absolute reference dose rate?
	Does it make (at least partly) use of the same algorithm as for relative dose computation?
	What is the detailed formulation (or mathematical expression) to account for the following: Influence of the shielding tray? Influence of the collimator opening and inversion of x and y (output factors)? Influence of the collimator asymmetry? Influence of wedges as a function of collimator setting (especially dynamic wedges)? Influence of shielding blocks? Influence of the MLC?
Plan dose normalization	Is it possible to normalize the accumulated dose distribution (i.e. for all beams)?
	What are the various options and methods for the calculation of the normalization factor?
	Is it possible to understand how the normalization is used for the different displays? In the various calculation planes? For 3-D display? For DVHs?

(b) An appropriate value for the dose rate constant;
(c) A proper calculation of the geometrical relationship between the source and calculation point.

These points are discussed further below.

The simplest form of a brachytherapy dose calculation is an interpolation from tables describing the dose rate distribution from an individual source. The tables are obtained from measurements or from some other type of calculation (e.g. Monte Carlo). Such tables are typically normalized for sources of strength equal to unity.

The formalism used in most TPSs consists of starting from the air kerma rate at a given reference distance (which is the modern replacement quantity for activity). A number of corrections are then applied to this quantity to include considerations related to geometry and tissue influence. The geometrical factor depends on the shape of the radioactive source. It is for a point source simply the inverse square of the distance to the source.

4.5.2. Dose from point sources

In spite of the many different solutions found in various TPSs, in this report only two formalisms are described: the modern formalism described by American Association of Physicists in Medicine (AAPM) Task Group 43 (TG 43) [54] and an older activity based formalism, illustrated by one example taken from Ref. [55]. However, it is highly recommended that the more modern TG 43 formalism be used, if at all possible.

4.5.2.1. Activity based method

For a source of small dimensions (i.e. a seed), brachytherapy dose calculations were originally based on the source activity from which the exposure rate in air ($\Delta X/\Delta t$ in roentgen/h) at some distance was derived according to:

$$\frac{\Delta X}{\Delta t} = (\Gamma_\delta)_x A_{\text{app}} \left(\frac{1}{r^2} \right) \tag{1}$$

where

$(\Gamma_\delta)_x$ is the specific gamma ray constant or exposure rate constant, in $R \cdot cm \cdot h^{-1} \cdot mCi^{-1}$.

A_{app} is the apparent activity (mCi). In the past, activity has sometimes been also specified using milligram radium equivalent. Note that there has been great confusion between contained and apparent activity.

r is the distance (cm) from the source to the point.

If the attenuation and scattering in the medium are ignored, then the dose rate to the medium can be obtained by multiplying the exposure rate in air by a conversion factor from R to cGy in the medium f_{med}. The more general expression for the dose rate to the medium, in the case of an anisotropic source, is:

$$D(r) = \left(\frac{A_{app} \left(\Gamma_{\delta} \right)_x}{r^2} \right) f_{med} T(r) \bar{\phi}_{an}(r) \tag{2}$$

where

$T(r)$ is the radial attenuation and radial multiple scattering effects in the medium;

$\bar{\phi}_{an}(r)$ is the anisotropy constant at a given distance r, averaged over all directions.

Since the calibration of modern sources is never based on a direct measurement of activity but on a measurement of air kerma at a reference distance (replacing a measurement of exposure rate), it has been suggested to use the result of this measurement to specify the strength of the sources. This replaces the above multiplication of activity by an exposure rate constant that was subject to a risk of major misinterpretation in the choice of a proper definition for activity and a proper constant value for dose computation [37, 56–60].

4.5.2.2. TG 43 formalism

According to TG 43 [54], the dose from a point source can be expressed as:

$$D(r,\theta) = S_k \Lambda \frac{1}{r^2} g(r) F(r,\theta) t_{eq} \tag{3}$$

where

$D(r, \theta)$ is the dose at distance r of a quasi-point source along the radius at angle θ;

S_k is the strength of the source expressed as air kerma rate ($\mu Gy \cdot h^{-1} \cdot m^2$, or U, where U is one unit of air kerma strength);

Λ is the dose rate constant ($cGy \cdot h^{-1} \cdot U^{-1}$);

$g(r)$ is the radial function that accounts for tissue attenuation and scatter;

$F(r, \theta)$ is the anisotropy correction function at distance r and angle θ;
t_{eq} is the application time, corrected for source decay.

As stated above, one of the most critical issues in the calculation is the source strength. It is therefore strongly recommended to express the source strength S_k in terms of air kerma rate, in order to avoid any misinterpretation of activity (expressed formerly in mCi, and now in Bq) that could be considered to be enclosed within the source envelope or equivalent to an unfiltered source yielding the same dose rate. In any case, some simple tests will resolve most ambiguities (see Section 9.5).

Except for low energy gamma emitters (below 200 keV) such as ^{125}I and ^{106}Pd, the correction factors $g(r)$ and $F(r, \theta)$ are not very different from 1 and therefore are not very critical. Conversely, however, they must be selected with great care for low energy gamma emitters. On the other hand, the anisotropy function is often averaged over all angles and furthermore over all distances, yielding average factors such as the anisotropy factor $\phi_{an}(r)$ and the anisotropy constant $\overline{\phi}_{an}$.

The application time t_{eq} is the integration time for a fixed distance between the source and calculation point, corrected for source decay according to the expression:

$$t_{eq} = \frac{(1 - e^{-\lambda t})}{\lambda} \tag{4}$$

where

t is the total integration time and is $1/\lambda$ the mean life of a radionuclide of half-life T:

$$1/\lambda = T/\ln 2 \approx 1.44T$$

When the application time t is short relative to T, $t_{eq} \approx t$. For permanent implants, $t_{eq} = 1/\lambda$.

Beyond the application of activity based or TG 43 formalisms, other methods for dose calculation are possible, but they are not described here. For the time being, Monte Carlo algorithms are too slow to be really useful clinically. However, they are invaluable for obtaining the proper values for data such as Λ, $g(r)$ or $\phi_{an}(r, \theta)$ [61, 62].

4.5.3. Dose from tubes or wires

For a non-point source, the expression for a point source has to be integrated along the active volume of the source. The integration can be done using a discrete summation or some mathematical approximation. For a rectilinear source of active length l, the integration of the geometrical factor for a point source ($1/r^2$) yields a geometrical factor equal to $\alpha/(lh)$, where α is the viewing angle at point P (expressed in radians), which covers the active part of the source, and h is the distance from P to the axis of the source.

If $g(r)$ and $F(r, \theta)$ are assumed to be independent of the distance of P to the source elements and approximated by $g'(r_c)$ and $\phi'_{an}(r_c)$, where r_c is the distance from P to the centre of the rectilinear source [63], the dose at P can be expressed as:

$$D = \frac{S_k}{l} \Lambda' \frac{\alpha}{h} g'(r_c) \phi'_{an}(r_c) t_{eq} \quad (5)$$

This expression is not fully consistent with the TG 43 formalism, since the three factors Λ, $g(r)$ and $\phi_{an}(r)$ are in principle closely interrelated and depend upon the source geometry. The symbols Λ', $g'(r)$ and $\phi'_{an}(r)$ have therefore been used instead, with slight modifications of the corresponding definitions (see also appendix B in Ref. [59]). This expression is, however, readily usable in TPSs, especially if sources of different lengths, such as iridium wires or intravascular sources, are being used (see also Refs [64, 65]). Although the above expression does not account properly for oblique filtration through the source and its wall, an anisotropy function $F(r_c, \theta)$ could be substituted to the anisotropy factor to include this effect. In addition, it must be recognized that it is not valid on the source axis, for which another expression must be used.

For a flexible wire, which could have any shape, the simpler approach is to consider it as a series of adjacent rectilinear sources.

4.5.4. Dose for stepping sources and optimization

The expressions above are also valid for stepping sources, considering sequentially each source position and using as t_{eq} the dwell time of each individual position. The use of stepping sources is often correlated with some optimization process that calculates the optimal source position and/or dwell time to meet a number of criteria on the dose distribution. These algorithms are very specific, and users must ask for appropriate information from the vendor.

5. QUALITY ASSESSMENT

5.1. INTRODUCTION

QA comprises all those planned and systematic actions necessary to provide adequate confidence that a product will satisfy given requirements for quality. QC includes a process of comparing measurements to existing standards. Thus there are several steps in the QC process: (a) the definition of a specification; (b) the measurement of performance associated with that specification; (c) the comparison of the measurement with the specification; and (d) the possible action steps required if the measurement falls outside the specification. As part of step (d), one needs to define what is an acceptable deviation (a tolerance) from the known standard. The following section discusses issues associated with measurements and quality assessment, including uncertainties, tolerances and errors.

5.2. UNCERTAINTIES, DEVIATIONS, TOLERANCES AND ERRORS

5.2.1. Uncertainty

Since no measurement or procedure in radiation treatment, including dose calculations, can be performed perfectly, each has a corresponding uncertainty. This uncertainty is a parameter that characterizes the dispersion of values that can be obtained for a particular measurement when it is performed repeatedly [66]. For such repeated measurements, the results can be represented by a statistical distribution (Fig. 10(a)), which can be summarized by specific statistical quantities such as mean, mode, standard deviation and variance. Uncertainty is the standard deviation (or multiples of it). A recognition and understanding of the uncertainties associated with the various stages of the radiation treatment planning process is necessary to determine the resultant uncertainty of the calculated dose distribution.

The uncertainty of the result of a particular measurement generally consists of several components that the Comité international des poids et mesures (CIPM) groups into two categories according to the method used to estimate their numerical values: Type A uncertainties are those that are evaluated by statistical methods and Type B uncertainties are those that are evaluated by other means. While in the past Type A and Type B uncertainties were classified as random or systematic, it is now recognized that there is not always a simple correspondence between these classifications. The radiation

therapy literature still uses the terms ‘random’ and ‘systematic’ uncertainties frequently. Indeed, systematic, as related to patient set-up, can be determined by statistical means and can be corrected for (e.g. after portal imaging measurements in the first few treatments). Figure 10(b) demonstrates an example of two uncertainty distributions, one of which has a systematic error.

5.2.2. Deviation

The deviation of a measured or calculated result is the difference between its value and the expected value obtained from some other method, and is considered to be a reference. As is discussed below, in the case of dose calculations the reference data are often obtained from measurements or from Monte Carlo calculations.

Contrary to measurements, which are subject to both Type A and Type B uncertainties, calculations are, in most cases, subject only to Type B uncertainties; for example, if one evaluates the dose calculated at one point then one will find that the calculation will be completely repeatable, assuming that the calculation parameters are identical (i.e. the same grid spacing, the same geometry, identical calculation point, identical calculation algorithm, etc.). However, when one performs a measurement at the same location in a phantom on a number of occasions, one will find a distribution of results. Thus the comparison is a calculation with zero random uncertainty with a measurement that will have a noticeable statistical distribution. If the calculation deviates significantly from the mean of the measured data, it is considered to have a systematic error (see below). In some cases, calculations

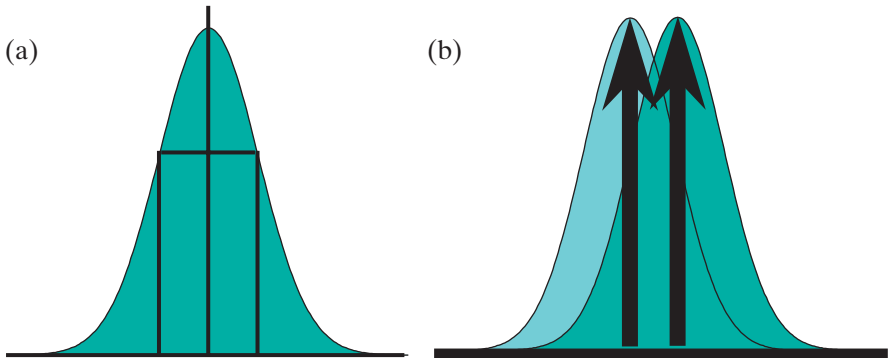

FIG. 10. (a) Uncertainty distribution for a particular measurement (vertical is frequency, horizontal is the measurement value); (b) comparison of uncertainty distributions, one about the proper mean and the other with a systematic error.

can also be subject to Type A uncertainties if they are based on a statistical method (i.e. Monte Carlo calculations) that makes use of random starting points (seeds) for the generation of random numbers.

In addition, one can also compare a number of calculation points (different spatial locations, for example central axis per cent depth doses) with a number of different measurements at the same spatial locations. It is then necessary to combine statistically the individual deviations to make an overall assessment of the quality of the calculation.

5.2.3. Tolerance

Tolerance is strictly defined as the range of acceptability beyond which corrective action is required. Thus if a measurement, for example the SSD, is given a tolerance of 5 mm, then any measurement outside the SSD ± 5 mm range literally cannot be tolerated (i.e. it is unacceptable and needs corrective action). However, as explained in Section 5.3, when considering TPSs, the situation is not straightforward and a looser definition is often used.

The choice of a tolerance value can be dependent on the uncertainty attributed to the reference data. It should be larger for larger uncertainties and can also be dependent on the specific application or protocol; for example, radiosurgery will have smaller tolerance in dose and geometry than palliative radiation treatments. It should be noted that a defined tolerance level within the radiation therapy context could be dependent on the clinical situation. Thus the tolerance levels associated with small field treatments as used for stereotactic radiosurgery will be substantially tighter than those for conventional or large field treatments, since stereotactic treatments involve very high doses given in a single fraction (or a few fractions for stereotactic radiation therapy), usually near very radiosensitive normal tissues.

5.2.4. Error

In the present context, an error is the deviation of a given quantity following an incorrect procedure. Errors can be made even if the result is within tolerance. However, the significance of the error will be dependent on the proximity of the result to tolerance, with errors near tolerance having relatively small significance and errors outside the tolerance range being of more concern, and effectively unacceptable.

Uncertainties of a random nature from different sources are generally added in quadrature. However, if there is a systematic error, then as a first consideration the error should be eliminated. However, in some situations the user knows that a systematic error exists but may not have control over the

elimination of the error. This is typical for a TPS for which the dose calculation algorithm may have a reproducible deviation from the measured value at certain points within the beam (e.g. at points in or near the penumbra region). Thus, while it is recognized that there is a reproducible difference, the user may not be able to adjust for this difference without causing larger differences elsewhere.

Known errors in TPSs that are outside the tolerance need to be reported immediately to the vendor. It is hoped that errors of significant clinical impact will be repaired and that the vendor will provide appropriate software updates. During the time that the error exists and the user needs to continue to use the TPS, the user must ensure that the particular situation exhibiting the error receive additional interpretation (i.e. manual correction) for clinical treatment planning.

5.3. QUALITY STANDARDS, REFERENCE DATA, TOLERANCES AND METHODS OF ASSESSMENT FOR A TREATMENT PLANNING SYSTEM

5.3.1. Quality standards

As defined in Section 5.1, in order to set up a QA programme for TPSs it is necessary to implement QC actions that require the definition of standards. Quality standards are the criteria against which any form of activity can be assessed. Standards can be defined in various forms, including those that have binary outcomes. Thus, for TPSs, if the specification includes the capability of generating DVHs, then the first assessment relates to functionality (i.e. does it perform DVH analysis?). The next level of assessment is the determination of the accuracy of the DVH analysis. Does it determine volumes to within an accuracy of 0.5 cm^3 or 1% at the level of one standard deviation?

Generally speaking, the quality assessment of a TPS implies a detailed screening of all features, which involves both qualitative and quantitative analysis. The following concentrates on the dose calculation feature.

5.3.2. Reference data

Reference data for the assessment of the quality of dose calculations have to be consistent with the beams actually used for treatments. Therefore, in principle, they consist of measurements performed by the user in a number of points and situations. These measurements are then used to evaluate deviations of dose computations for similar conditions and are referred to as beam

reference data. However, beyond the basic comparison, and especially for complex cases, it is possible to devise other methods that make use either of benchmark data, obtained with generic beams, published in the literature, or arbitrary data if the assessment is based on internal consistency. A last category of reference data is related to the set of data required for beam parameterization and is referred to as algorithm input data. Table 16 summarizes these various types of reference data.

However, when specifications are quoted for a given TPS, they are often ambiguous; for example, when a vendor indicates that "the dose calculation algorithm is accurate to 2%", does this mean that the maximum difference with experiments or Monte Carlo calculations is 2%, or that the standard deviation of the differences is 2% (in which case some differences at specific points can be much larger than 2%) or some other statistical parameter? A manufacturer's statement of accuracy should therefore include these statistical considerations [24].

5.3.3. Tolerances for dose calculations

The tolerance considerations are:

(a) There are differences between measurements and calculations.
(b) These differences are dependent on the location within the beam and on the patient geometry.
(c) One cannot make simple statements about criteria of acceptability (tolerances). It is well recognized that the accuracy of dose calculations depends on the algorithm, the region within the beam (Fig. 11) and the region within the patient. One must therefore analyse deviations (and set tolerances) with this understanding in mind.
(d) A useful way to compare calculations and measurements is to analyse the deviations statistically. Although a given tolerance may be assigned to individual point value comparisons, the decision of overall acceptability is not based on strict adherence to the tolerance at each point. Rather, decisions are based on confidence limits or other similar criteria; for example, a few points may fail to meet a tolerance of 2%, but this may be acceptable if 95% of points fall within 2%.
(e) Any general table of tolerances or expectations depends on the state of the art of the dose calculation algorithms and on the types of situation (beams, patients) considered. Different users can look at the same types of information and decide on different values for expectations or tolerances. Two different examples of methods for defining criteria of acceptability are illustrated in Tables 17 and 18.

TABLE 16. TYPES OF REFERENCE DATA

	Description
Algorithm input data	The algorithm input data required for beam parameterization, usually specified by the vendor
Beam reference data	Data measured to evaluate the quality of the dose calculation
Benchmark data	Published benchmark data from other workers, such as a reference set of data for inhomogeneity dose calculation test cases
QA reference data	Calculation results that become the reference data, which are used for future QA tests

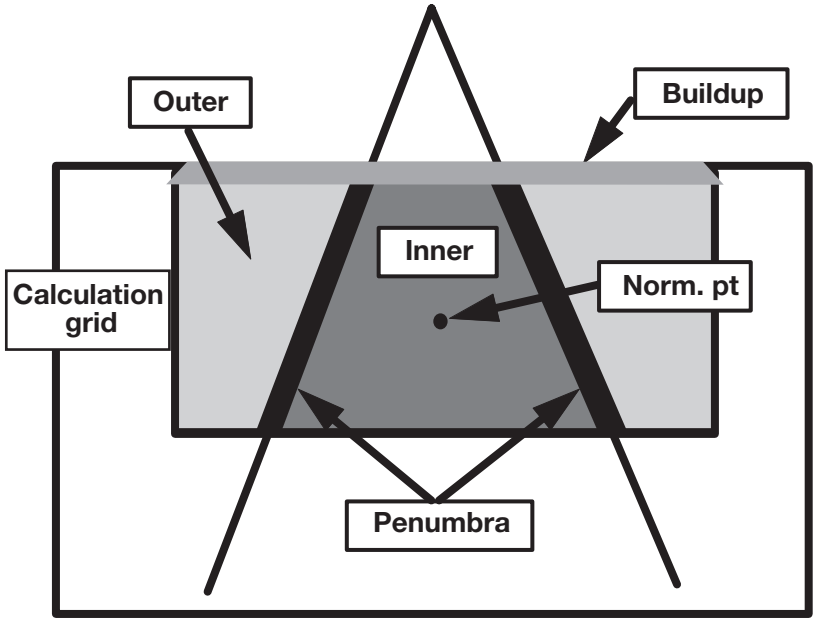

FIG. 11. Regions of different accuracy capabilities for photon beam dose calculations. Reproduced, with permission, from Ref. [18].

Deviations between results of calculations and measurements (i.e. beam reference data) can be expressed as a percentage of the locally measured dose [67]:

$$\delta = 100 \times \frac{(D_{calc} - D_{meas})}{D_{meas}} \quad (6)$$

where

δ is in per cent;
D_{calc} is the calculated dose at a particular point in the phantom;
D_{meas} is the measured dose at the same point in the phantom.

In this case some statistical assessment can be performed on the calculation points and the measurement points.

Venselaar et al. [67] have defined a set of criteria of acceptability based on different tolerances for δ based on the knowledge that dose calculation algorithms provide better accuracy in some regions of the beam than in others (Fig. 11). Such regions of different criteria of acceptability have been defined previously [18, 19, 23]. Figure 11 is from AAPM TG 53 [18] and gives a schematic representation of these different regions. Figure 12 is from Venselaar et al. [67] and shows dose comparisons in these regions by plotting dose versus depth (Fig. 12(a)) and dose versus distance across the beam (Fig. 12(b)). A summary of the tolerance values for the different δs proposed by Venselaar et al. [67] is shown in Table 18.

5.3.4. Confidence limits

The deviations, δ, described above refer to comparisons of individual calculated and measured points. Venselaar et al. [67] refer to the δs as

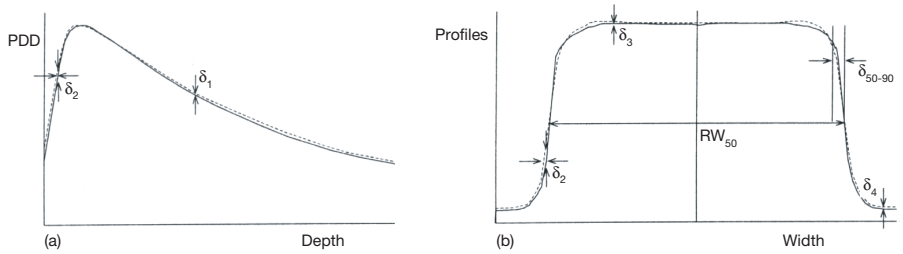

FIG. 12. Regions of different accuracy capabilities for photon beam dose calculations. Reproduced, with permission, from Ref. [67]. (a) Dose versus depth; (b) dose versus distance across the beam.

TABLE 17. SAMPLE CRITERIA OF ACCEPTABILITY FOR EXTERNAL DOSE CALCULATIONS
(Adapted, with permission, from Ref. [18].)

Situation	Absolute dose at normalization point (%)[a]	Central ray (%)	Inner beam (%)	Penumbra (mm)	Outer beam (%)	Buildup region (%)
Homogeneous phantoms						
Square fields	0.5	1	1.5	2	2	20
Rectangular fields	0.5	1.5	2	2	2	20
Asymmetric fields	1	2	3	2	3	20
Blocked fields	1	2	3	2	5	50
MLC shaped fields	1	2	3	3	5	20
Wedged fields	2	2	5	3	5	50
External surface variations	0.5	1	3	2	5	20
SSD variations	1	1	1.5	2	2	40
Inhomogeneous phantoms[b]						
Slab inhomogeneities	3	3	5	5	5	—
3-D inhomogeneities	5	5	7	7	7	—

Note: Percentages are quoted as per cent of the central ray normalization dose.
[a] Absolute dose values at the normalization point are relative to a standard beam calibration point.
[b] Excluding regions of electronic disequilibrium.

tolerances, although this is not strictly correct. If a study consisting of many points is evaluated, some of these points may exceed the tolerance, but the overall accuracy result may be satisfactory. This occurs, for example, when data points along the central axis are evaluated or when dose points on a dose profile across the beam are compared. For cases in which many such points are

TABLE 18. EXAMPLE ILLUSTRATING DEVIATIONS (δ) FOR DIFFERENT REGIONS

(Adapted, with permission, from Ref. [67].)

	Location	Type of region	1. Simple geometry (homogeneous)	2. Complex geometry (wedge, inhomogeneity, asymmetry)	More complex geometry (combinations of 1 and 2)
δ_1	Central beam axis	High dose, small dose gradient	2%	3%	4%
δ_2[a]	Buildup region of central axis and penumbra region of profiles	High dose, large dose gradient	2 mm or 10%	3 mm or 15%	3 mm or 15%
δ_3	Outside central beam axis region	High dose, small dose gradient	3%	3%	4%
δ_4	Outside beam edges	Low dose, small dose gradient	3%[b] (30%)	4%[b] (40%)	5%[b] (50%)
RW_{50}[a]	Radiological width		2 mm or 1%	2 mm or 1%	2 mm or 1%
$\delta_{50\text{-}90}$	Beam fringe		2 mm	3 mm	3 mm

[a] These values are preferably expressed in mm. A shift of 1 mm corresponding to a dose variation of 5% is assumed to be a realistic value in the high dose, large dose gradient region.

[b] This percentage is applicable to the following equation, $\delta_4 = 100\% \times (D_{calc} - D_{meas})/D_{meas,cax}$, where $D_{meas,cax}$ is the dose on the central beam axis, since it is not always practicable to compare with the local dose. The values in brackets are those determined from Eq. (6).

compared, Venselaar et al. [67], based on the work of Welleweerd and Venselaar [68], defined the confidence limit, Δ, as follows:

$$\Delta = |\text{average deviation}| + 1.5\text{SD} \quad (7)$$

where SD is the standard deviation.

Thus the tolerances as defined in Table 18 can be applied to the confidence limit Δ rather than to individual points. A system may fail to meet tolerance, either: (a) when the mean deviation of all the points is too large; or (b) when some points show large deviations and the SD is too large. While often a 95% confidence interval is chosen (i.e. a multiplication factor of 1.96SD), Venselaar et al. [67], somewhat arbitrarily, but based on their experience, chose a factor of 1.5SD to represent a *P* value of 0.065. A factor of greater than 1.5 would emphasize random (Type A) errors, while a factor of less than 1.5 emphasizes systematic (Type B) errors. In comparing seven TPSs, they found that tolerances of 3% could be used for most geometries, except for some of the more complex geometries, where 4% was generally found to work.

While the tolerance concept is useful, the issue of defining tolerances for medical physicists to use in the commissioning of TPSs has some significant practical difficulties that need to be recognized. At present, not all vendors of TPSs provide tools for performing the statistical analyses necessary to use the tolerance concept. Making quantitative and statistically valid statements about a system's capability is therefore at present impracticable. In this context it is strongly recommended that vendors provide the appropriate evaluation and analysis tools, perhaps using third party spreadsheet software.

An additional problem needs to be recognized. The calculated dose distribution is strongly dependent both on the parameterization performed by the user and on the dose calculation algorithm. Since the vendor provides the dose calculation software, the user may not be able to control situations in which the calculations are outside tolerance. While the user can inform the vendor of the situation, the user may have to wait until the vendor makes software changes before the calculations are within tolerance. In practice, what we can do now, in the absence of specific tools or the practical possibility of using the confidence limit concept, is to perform point calculations and measurements or 1-D profile measurements in which specific values are compared for analysis of agreement. This is generally done on a quantitative basis for a select number of points, but usually not using rigorous statistical sampling.

5.4. SOURCES OF UNCERTAINTIES AND LIMITATIONS FOR A GIVEN PLAN

Uncertainties inevitably are present at every stage of the treatment planning process, and these could have an impact on the accuracy of the treatment plan and on the final treatment. In order to set realistic tolerance

TABLE 19. EXAMPLES OF UNCERTAINTIES ASSOCIATED WITH THE USE OF A TREATMENT PLANNING SYSTEM

	Uncertainty consideration
Basic beam data	Measurement uncertainties (detector reading reproducibility) Detector resolution Detector sensitivity
Input–output devices	Digitizer co-ordinate location uncertainties Generation of contours from CT films Density assumptions when CT films are used for contours Image display resolution Inaccurate location of isodose lines on the display (an inaccurate display could result in an inaccurate placement of beams)
Data transfer	Inaccuracies relate to how the software writes and reads the data, especially for CT and MR scanners
Individual patient data	Reproducibility of patient set-up Organ motion during the different steps of the planning and treatment process Use of different imaging modalities, each with their own capabilities and limitations, for example MR distortions
Target volumes and beam parameters	Inter- and intraobserver variability in defining target volumes (different target volume definitions could result in a different choice of field sizes or even different optimization techniques)
Dose calculation limitations	Algorithms provide an approximate solution to complex physics Accuracy varies depending on the circumstances Deviations tend to be systematic Choice of calculation parameters such as grid spacing and pencil beam size have a significant impact on accuracy
Plan evaluation limitations	DVH accuracy is affected by the accuracy of volumes or doses DVH accuracy is dependent on the number and location of points used for DVH determination

levels, one must have knowledge of the uncertainties such that the tolerance level will be achievable. Table 19 summarizes some of the uncertainties associated with the use of TPSs.

6. QUALITY ASSURANCE MANAGEMENT

6.1. QUALITY MANAGEMENT PROCESS

Section 1.7 introduced the concept of TQM and indicated that this comprises much more than dealing with individual procedures and technologies. It is really an institutional focus that begins with the management at the top of the organization and should be pervasive throughout the organization. The radiation treatment programme should have a QA committee that oversees the overall QA activities within the programme. An example reporting structure of such a committee is shown in Fig. 13 [32, 69]. Treatment planning quality management is a subcomponent of the TQM process. Organizationally, it involves physicists, dosimetrists, radiographers (radiation therapists and radiation therapy technologists) and radiation oncologists, each at their level of participation in the radiation treatment process. Treatment planning quality management involves the development of a clear QA plan of the TPS and its use.

6.2. TREATMENT PLANNING QUALITY ASSURANCE PLAN

The middle column of Fig. 14 summarizes the steps in the process flow of the radiation treatment planning process, although not all the steps are always in the order shown. The left column shows the individuals involved in the process and the right column shows specific procedures that relate to QA action items. Every radiation therapy organization should develop a treatment planning QA plan. Figure 14 provides an idea of the components that should be included in a plan, although it is not comprehensive in that it does not show every possibility of the process.

6.3. PHYSICIST RESPONSIBLE FOR THE TREATMENT PLANNING SYSTEM

The medical physics department is responsible for the QA of the TPS and the use of its output. The institution should appoint one medical physicist to be responsible for all aspects associated with the TPS in the institution [18]. This person may need extra training and should be responsible for the following activities:

(a) Providing overall supervision of the use of the TPS.
(b) Providing maintenance and security of the TPS, and associated work.
(c) Performing and/or supervising the commissioning process.
(d) Acquiring a full understanding of the operation of the hardware and software.
(e) Maintaining a logbook during commissioning and during routine use after commissioning. The logbook should document all the events and changes concerning the TPS, including the system history (software and hardware upgrades), QA procedures and records, and vendor and user bug reports.

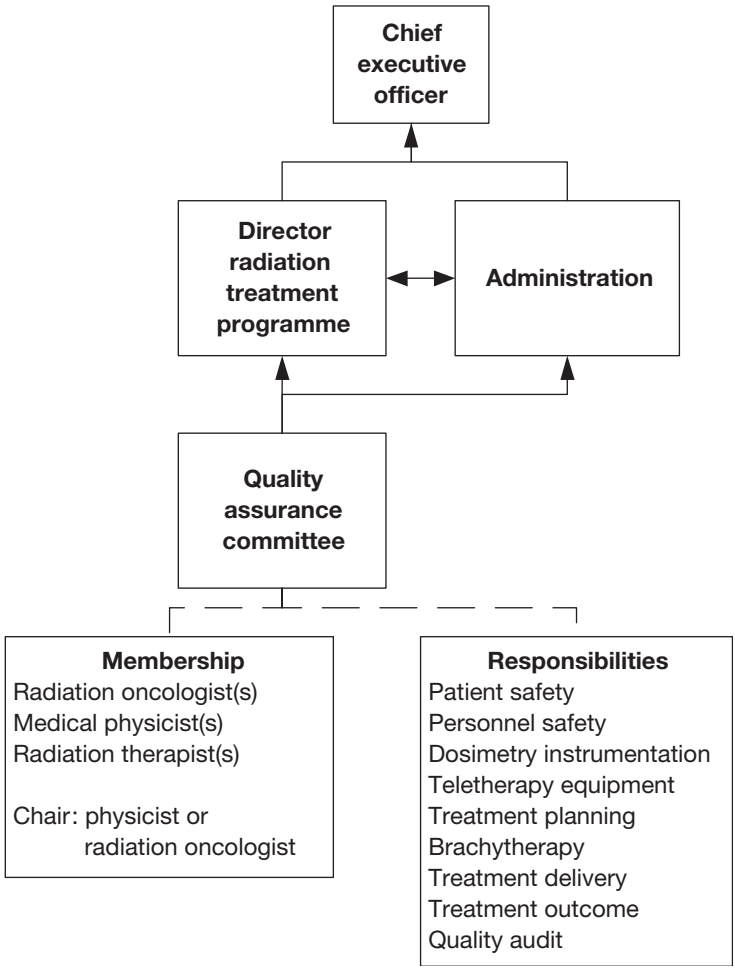

FIG. 13. Example reporting structure of a QA committee. Adapted, with permission, from Ref. [32].

(f) Controlling the beam library.
(g) Introducing new or updated TPS software.
(h) Supervising TPS hardware changes.
(i) Providing training for staff, including physicians and planners.
(j) Performing systems management or supervising the activities of the computer systems manager.
(k) Communicating with the vendor.
(l) Participating in users' groups, where possible.
(m) Maintaining and revising the QA programme.

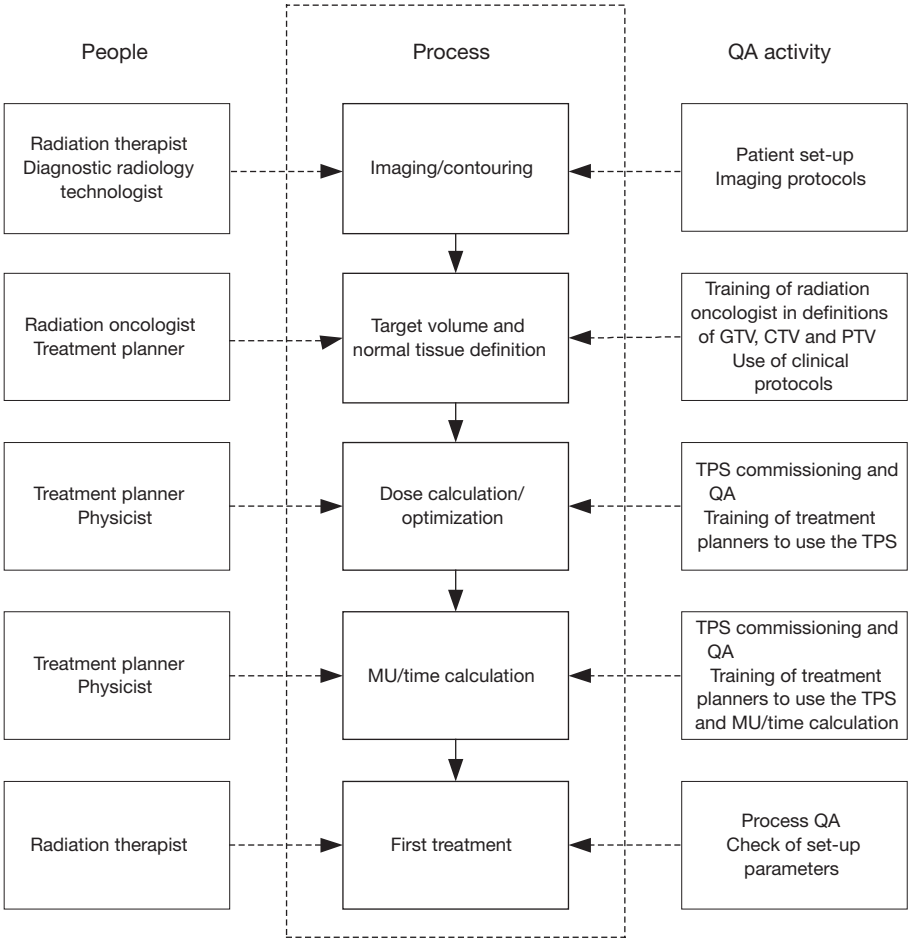

FIG. 14. Steps of the treatment planning process, the professionals involved in each step and the QA activities associated with these steps.

Note that it is not essential that one person carry out all the QA work; however, it is important that one person have overall control and responsibility. Thus, for example, any user might perform some of the regular checks, but the responsible physicist is fully accountable. There must, however, be enough redundancy or backup within the radiation treatment programme that the tasks and responsibilities of this individual are maintained in the event of his or her absence.

6.4. PERSONNEL

The greatest risk of malpractice lies not in sudden or even gradual changes in the performance of the TPS, but in human error. Mismanagement of beam data files, misuse of the software, introduction of inappropriate planning practices and inadequate training of users are some of the ways in which the quality of treatment planning can be compromised. Proper and safe treatment planning can only take place with the right number of people who have the right skills.

Owing to its complexity, 3-D treatment planning technology requires more effort to implement, and therefore more staff, than a conventional 2-D TPS. The commissioning and implementation of an extensive QA programme could involve medical physicists, dosimetrists, radiation therapists, physics technicians and computer personnel. The actual number of people required and their expertise depends on the size of the radiation treatment programme and on the complexity of the treatments used. However, it is essential that there be sufficient staff to ensure that the system is used safely and that the QA programme can be followed routinely.

Depending on the complexity of the TPS, it may be necessary also to designate a second person, with skills in computer hardware, operating system software and networking, as a computer systems manager. This person should be accountable to the physicist managing the TPS.

There must be a level of redundancy in management. Regardless of the size of the department, it is dangerous for only one person to hold vital information about the TPS. It should be ensured that someone else is familiar with the system's hardware, passwords, file structure, backup and recovery procedures, basic troubleshooting and whom to contact in the event of a breakdown.

Staff using the planning computer should have experience and demonstrated competence in both treatment planning and systems operation.

6.5. COMMUNICATION

Open communication is an integral component of the QA process. This communication should take place between all the staff involved in the treatment planning process, including radiation oncologists, medical physicists, radiation therapists and dosimetrists. All staff should be encouraged to ask questions when in doubt about:

(a) Any step in the QA process;
(b) Any activity or aspect associated with an individual patient's treatment, including issues related to patient set-up or ancillary devices;
(c) Any information on the treatment chart or the treatment plan.

Treatment errors can readily be avoided by using a system whereby individuals are encouraged to ask questions.

6.6. EQUIPMENT

Much of the equipment needed to commission a TPS overlaps with the equipment needed to commission a megavoltage therapy machine such as a linear accelerator or a ^{60}Co unit. The types of equipment needed for a TPS are summarized in Table 20. Which equipment is purchased by any one institution will depend on the resources available, the complexity of the treatment planning and the complexity of the corresponding treatments.

It is beyond the scope of this report to give detailed recommendations on how measurements should be performed and on which physics concerns need to be addressed for different detectors. Such information can be found in, for example, Ref. [70]. However, some issues are particularly relevant to the generation of data for TPSs. It is especially important for the purchaser of a TPS to understand which types of data are required for the commissioning of a system and how these data will be entered into the TPS; for example, if the entry of the measured data into the TPS is performed through a network connection or via some magnetic media, it is important to ensure compatibility of the TPS software and the software of the (computerized) water phantom scanning system. Furthermore, a QA programme for the measuring equipment must also be instituted. Accurate data acquisition by any beam data acquisition system (BDAS) requires that the unit be subjected to a systematic performance test prior to use. Any computations performed by the BDAS must be compared with a sampling of manual calculations carried out with the same

TABLE 20. BASIC EQUIPMENT SUGGESTED FOR THE COMMISSIONING AND QUALITY ASSURANCE OF A TREATMENT PLANNING SYSTEM

Equipment	Purpose
CT scan test phantom	CT number to electron density conversion Beam geometry assessments DRR generation Multiplanar reconstructions
Water phantom scanning system (also known as BDAS)	Measurement of central axis data Measurement of beam profiles
Detectors	
Cylindrical ionization chambers	Measurement of absorbed dose to water in reference conditions Measurement of central axis depth doses Measurement of beam profiles
Diodes and small ionization chambers	Measurements in high dose gradients, including penumbra and buildup
Parallel-plate chambers	Measurement in the buildup region on the central ray for photon beams
Film	Measurement of central ray data for electron beams
Thermoluminescent dosimeters or MOSFET dosimeters	Dose profiles, 2-D dose distributions and electron beam dosimetry Special phantom (anthropomorphic) measurements In vivo dosimetry
Electrometers	For output from ionization chambers or diodes
Thermoluminescence dosimetry (TLD) readout system	Required for TLD measurements
Phantoms	
Slab geometry	Water or tissue equivalent
Water or tissue equivalent	For film dosimetry
Low density (cork or wood)	For inhomogeneous geometries
Anthropomorphic	For TLD measurements of typical or special treatment techniques
Linear detector arrays (LDAs) and ionization chambers or diodes	For measurement of profiles, especially for dynamic wedges and IMRT
Film densitometer	For film dosimetry

data. Hard copy output, both numerical printouts and plots, needs to be evaluated for accuracy as well as correctness and completeness in labelling.

6.7. STAFF TRAINING AND EDUCATION

The complexity of 3-D treatment planning technology necessitates highly trained personnel. While a system could be functioning perfectly, an error in user input can generate major errors in output. Training is therefore imperative to ensure the safe use of the TPS. Training is required at various levels.

Early in the process of TPS acquisition, a decision should be made about additional training for the departmental staff [25]. A plan to train these personnel prior to the TPS installation should be developed. This plan should include information on who will be trained, the host institution that will provide the training and when the training will occur. The training should not only be for those individuals with hands-on use of the TPS but also for those who will interpret the data that come out of the TPS, including, for example, the radiation oncologists and the radiation therapists on the treatment machines. The vendor should provide high quality training for the operators.

The manufacturer's training course should include:

(a) Teaching of the functions of the system;
(b) Planning strategies;
(c) Additional training for the responsible physicist on the algorithms, system architecture and simple hardware maintenance.

Prior to commissioning, the physicist responsible for treatment planning and the overall supervision of the TPS, together with the computer systems manager, if there is one in the department, should be given proper operational training to become familiar with the software and the operating system. Special training should be provided for the physicist who deals with beam data entry, the fitting process and calculation verification.

Prior to clinical use, all staff performing clinical treatment planning must be appropriately trained for the functions they will perform. Training for sophisticated 3-D systems should not only include teaching the operators what the effect of a particular operation will be, but also include useful strategies for planning [18].

Ongoing training is required after the installation of the TPS. After the system is placed into clinical service, training becomes an important part of the ongoing QA. Continuing education is essential for all staff members, as it is undoubtedly one of the best ways to ensure quality durability. Heads of

departments must devote sufficient funds and encourage continuing education. In addition, there should be in-house training for the physicians, since they need to understand precisely what input information is required by the treatment planning computer. Furthermore, it is also beneficial for the radiation oncologists and treatment planners to have knowledge of the ICRU prescription recommendations [35] (i.e. the definitions of the GTV, CTV and PTV). Again, consistency by all physicians and treatment planners will reduce the probability of errors and will ensure consistency with other published clinical procedures and clinical results.

Usually only a limited number of staff will have been able to benefit from the vendor's initial training. It is vital that skills and understanding be passed on to subsequent users, and wherever possible there should be an overlap period when staff change. It is good practice, particularly for staff in smaller centres, to cross-check their understanding and use of the system with other users, either via formal users' meetings or informally. A regional list of customers can usually be obtained from the vendor.

New staff should be trained and they should have their work checked by a qualified person before using the system clinically. New or previously unused software or beam data should not be introduced to the clinic until staff have been trained to use it and until the documentation is updated.

6.8. COMPUTER SYSTEMS MANAGEMENT AND SECURITY

The responsible physicist and the systems manager should maintain clear records of which versions of the software have been installed, with dates of installation. Furthermore, records should be kept of all the latest data files and their contents. A process of regular system backups needs to be developed to ensure that no patient data of any form are lost in the event of a computer software crash.

Security needs to be developed at several levels. Firstly, the system should be secure from outside intrusion through the network. Secondly, the system should be secure from users who are not qualified to use the TPS. Thirdly, the TPS and all its peripherals should be kept secure from theft. Theft is not only a problem from a cost perspective but also from the point of view of losing important and confidential treatment information. In addition, lost information may require patient replanning, which will impact upon departmental resources.

Access to the system should be restricted to those who are qualified to use it. Although it is common for systems to have password protection, sometimes with several levels of access, and even for each user to have his or

her own password, this in itself is not sufficient. Users must be trained to log out of the system on completing the session, ensuring that files are closed and access to others is denied. Passwords should not be written down in obvious places.

Planning systems that are networked together and integrated into a hospital's network can be accessed remotely. This is a considerable advantage for the systems manager, who can often perform housekeeping tasks from his or her office, but it does present an additional security risk. Remote access should be controlled carefully to prevent indiscriminate manipulation or deletion of files. Patient data, especially images, should not be accessible to outsiders. It is quite common for vendors to provide modem support for remote access, primarily for trouble shooting. While this can be an advantage, vendor access should be controlled and documented (i.e. the systems manager should know what has been changed, and why). In addition, computer security for the TPS and the machine control system must be carefully managed to provide a high level of security, preventing unwelcome and unexpected users from tampering with the data, the system set-up, the network or any other part of the systems in question.

It is important that data be backed up on a regular basis, either to an archive medium (e.g. tape) or to a separate (external or remote) hard drive. Current patient data should be backed up daily; other data and planning software only require infrequent routine backup. It is very important that the ability to recover data from the backup device also be checked regularly.

Any system that depends on electronic transfers of information between systems depends critically on the integrity of the communications protocols and on security. Although modern communications protocols such as Ethernet maintain a high level of hardware integrity, the overall security and behaviour of any networked systems should be checked routinely and confirmed.

6.9. POLICIES, PROCEDURES AND DOCUMENTATION

Documentation must be written in a language understandable to the user. It is important that documentation be practical, accessible and up to date. All vendors provide manuals and/or online help for their TPS. Once the vendor provides updated documentation, the documentation being replaced should be discarded immediately to avoid confusion. Although vendor documents are useful (although some are better than others), they are unlikely to cover a department's specific procedures for image transfer, planning for particular techniques, hard copy output required, backup, etc. It is good practice to detail

these in a separate manual, together with 'how to' information, to complement the supplied documentation.

Clear and documented policies and procedures should be developed for:

(a) Special treatment techniques;
(b) QA procedures, including plan checking and approval procedures, MU/time QA procedures, TPS ongoing QA and processes for software upgrades and recommissioning tests.

6.10. COMMON ERRORS

In developing a QA programme for a TPS it is useful to analyse potential sources of errors that might occur when using the system. This comes under the general principle of risk management. A reference was made in Section 1.4 to an IAEA report [4] that summarized 92 radiation therapy accidents that have been reported to regulatory authorities and professional associations, published in scientific journals or otherwise become known by publication. The intention was to learn from previous incidents and to develop a questioning and learning attitude, adopt measures of accident prevention and prepare for mitigation of the consequences of accidents if they occur. The following expands on some recognized areas of concern in the use of TPSs. While these are examples based on the authors' collective experience, they may or may not be based on previously published quantitative information.

6.10.1. Software misinterpretation

It is very important for the user to have a basic understanding of the software capabilities and software performance (see Section 4); for example, how is the wedge factor used in the dose calculation? Does the treatment planner need to include it in the MU calculation? The output factor for a dynamic (virtual) wedge is strongly dependent on the wedge direction when using asymmetric fields. Does the software handle this or does this need to be handled by an independent MU calculation process? For ^{60}Co output determinations, does the user need to account for source decay or is this handled automatically by the calculation? Is the user aware of where the field size is defined? This question ties in with the confusion that can occur with SSD versus source to axis distance (SAD) set-ups.

6.10.2. Normalization

It is essential to have a clear understanding of how dose distributions are normalized. Ultimately, it is this normalization that needs to be linked to the therapy machine MU/time calculation. Some systems always normalize the beam to 100% at a reference point for a flat contour and a homogeneous, water equivalent patient. Other systems normalize to a reference point and call it 100% accounting for surface curvature, field shape and inhomogeneities. Then, in the MU/time calculation, an appropriate correlation is developed for the calibration geometry. However, in all circumstances it is very important for the user to understand how his or her particular system is normalizing the dose distribution. Significant errors can occur under some conditions if this is misinterpreted.

6.10.3. Beam parameterization

Many systems derive specific parameters that are required for the dose calculation algorithm. These parameters are usually derived from measurements, although they could be derived from calculation once the system knows, for example, the beam energy specification. It is important for the user to understand how these parameters are derived and their significance in the dose calculations; for example, a collimator transmission factor may be derived from beam profile measurements at long distances from the beam edge. If the user does not measure data at long distances, the software could determine the transmission factor from the largest distance measurement or it could determine it by extrapolation. In either case, it is potentially subject to large errors, since inappropriate data were used to derive this parameter.

6.10.4. Monitor unit/time calculations

MU calculations for medical accelerators, time calculations for ^{60}Co machines and brachytherapy calculations are crucial end products of the treatment planning and dose calculation process. In the past, many TPSs performed relative dose calculations only and left the user to perform the time or MU calculation independent of the TPS. Modern TPSs generally provide automated MU/time calculation programs that use the data developed for the specific treatment plan. The MU/time calculation process must be clearly understood and compared with (approximate) manual calculations. Furthermore, it is important for the user to have entered all the correct factors for machine output and beam modifiers. Any errors in the interpretation of these factors will translate directly into errors in the number of MUs or the

treatment time calculated for specific patient treatments. As indicated in Section 1.4, a major series of patient treatment errors in one institution due to an improper use of a TPS resulted in very significant overexposure (by approximately a factor of 2) of 28 patients, at least five of whom died as a result of the overexposure.

6.10.5. Inhomogeneity corrections

The use of inhomogeneity corrections for tissue density variations has become standard practice in most radiation therapy departments that have direct access to CT scanning for radiation therapy planning. However, the procedure used by the TPS for performing the inhomogeneity corrections is occasionally not well understood by the user. Such misunderstandings often arise because of dose normalization. Ideally, all manufacturers would use the same procedures. In practice, however, owing to variation in calculation algorithms and variations in user and vendor preferences, there could be substantial differences of interpretation and implementation of inhomogeneity corrections in different TPSs.

6.10.6. Understanding software capabilities and limitations

In the use of TPSs it is important for the user to have a clear understanding of the system's capabilities and limitations. This is best achieved through rigorous training and a thorough implementation and commissioning of the TPS. The sources of information include: (a) system manuals provided by the vendor; (b) training courses provided by the vendor; (c) published literature on dose calculation algorithms; (d) comparisons of calculations with measurements for uniform phantom geometries; (e) comparisons of calculations with measurements for anthropomorphic phantom geometries; and (f) in vivo dosimetry. Furthermore, the user should communicate with other users of the same TPS to compare their experiences.

It must also be recognized that within one institution there could be users of the TPS who have different depths of knowledge about the system's capabilities and limitations. Thus the physicist responsible for the TPS should be a departmental resource for physicists, dosimetrists or radiation therapists (technologists) who may be involved in the routine treatment planning of patients.

6.10.7. Error management

It is impossible to eliminate the risk of error. As treatment planning becomes more sophisticated, the risk of error increases, in spite of embedded software warnings and interlocks.

An acceptable level of prevention is obtained by implementing the procedures described in this report, but it must be stressed that a very important aspect of prevention is to have a proper 'state of mind'. It is essential to recognize that computer calculations can be wrong due to erroneous input data and software bugs and to analyse all outputs with a critical eye. This attitude is only possible under two sets of conditions: (a) there needs to be adequate equipment and staff, both quantitatively and qualitatively; and (b) the staff need to have adequate training.

7. PURCHASE PROCESS

The purchase of a TPS is a major step for most radiation oncology departments. Particular attention must therefore be given to the process by which the purchasing decision is made. The specific needs of the department must be taken into consideration, as well as budget limits, during a careful search for the most cost effective TPS among the many alternatives on the market.

The following are some of the factors to consider in the purchase and clinical implementation process [25]:

(a) Assessment of need. The purchasing institution will have to define its specific needs for the TPS in advance. Factors to consider include:
   (i) The status of the existing system;
   (ii) The anticipated case load over the next few years;
   (iii) Whether special techniques such as high dose rate (HDR) brachytherapy or stereotactic radiosurgery will need to be performed;
   (iv) The number of workstations required;
   (v) The level of sophistication of treatment planning (e.g. 3-D conformal radiation therapy (CRT) or special needs for clinical trials);
   (vi) Imaging availability for treatment planning (e.g. CT and MRI);
   (vii) The availability of a CT simulator;
   (viii) The availability of an MLC;
   (ix) Brachytherapy considerations;

(x) IMRT requirements;
(xi) Anticipated treatment trends.

(b) Request for information. It is useful and educational to send out a request for information at an early stage to vendors of TPSs. This should include a request for technical specifications as well as a budgetary quotation. This will provide a basic understanding of what is available and the corresponding capabilities of the systems, as well as an approximate cost estimate.

(c) Vendor demonstrations. From the information provided by the vendors, it is possible to shortlist the vendors and to approach them for more detailed information. It is then useful to have detailed vendor demonstrations and to see the systems in use in a clinical environment.

(d) Tender process. It is useful to develop a detailed tender document requesting vendors to indicate their specifications, pricing, training, servicing, warranty, etc. See Ref. [25] for more details.

(e) Selection. A summary should be made of specific aspects of the system that are: (1) essential; (2) important; (3) useful; and (4) not needed. The use of these criteria and comparison of the capabilities of different systems will be useful in decision making.

(f) Purchase. Once a decision has been made regarding the preferred system, it is important to negotiate the best price and to develop a clear purchase document that outlines the purchase, including all the options, training and servicing. With respect to servicing, both software and hardware upgrade options need to be carefully considered, since both of these change at a very rapid rate.

Once the system is purchased, the commissioning and QA procedures described in Sections 9 and 10 of this report should be implemented.

7.1. ASSESSMENT OF NEED

The best way to define the needs of the department is to set up an equipment selection committee having representation from the physics, oncology and computer staff. This committee should address questions such as those listed in Table 21.

These questions will include such matters as the general patient types to be planned, imaging availability, the level of treatment complexity likely to be used, the specific types of radiation therapy equipment to be used in the department, the need for specialized planning procedures such as stereotactic

TABLE 21. FACTORS TO CONSIDER IN THE EARLY PHASE OF THE PURCHASE PROCESS FOR A TREATMENT PLANNING SYSTEM
(Adapted, with permission, from Ref. [25].)

Issue	Question and/or comment
Status of the existing TPS	Can it be upgraded? Hardware? Software?
Projected number of cases to be planned over the next 2–5 years	Include types and complexity, for example number of 2-D plans without image data, number of 3-D plans with image data, complex plans, etc.
Special techniques	Stereotactic radiosurgery? Mantle? Total body irradiation (TBI)? Electron arcs? HDR brachytherapy? Other?
Number of workstations required	Depends on caseload, average time per case, research and development time, number of special procedures, number of treatment planners and whether the system is also used for MU/time calculations
Level of sophistication of treatment planning	3-D CRT? Participation in clinical trials? Networking capabilities?
Imaging availability	CT? MR? SPECT? PET? Ultrasound?
CT simulation availability	Network considerations
Multileaf collimation available now or in the future	Transfer of MLC data to therapy machines?
3-D CRT capabilities on the treatment machines	Can the TPS handle the therapy machine capabilities?
Need for special brachytherapy considerations	For example, ultrasound guided brachytherapy Can ultrasound images be entered into the TPS?
IMRT capabilities	Available now or in the near future?
Treatment trends over the next 3–5 years	Will there be more need for IMRT or electrons or increased brachytherapy?
Case load and throughput	Will treatment planning become the bottleneck?

radiosurgery, HDR brachytherapy and ultrasound guided prostate implants, and the use of 3-D CRT, multileaf collimation, inverse planning, etc.

It is useful to make a summary list of standard procedures and specialized procedures and then to request the vendors to demonstrate how they can handle them.

Based on these answers, the committee will decide upon the general capabilities of the required TPS, the required number of treatment planning

stations and the necessary interfacing and/or networking with appropriate diagnostic scanners or CT simulators.

7.2. REQUEST FOR INFORMATION

When making a decision on the purchase process, the department should request pertinent information from all TPS vendors. This request should include system specifications and capabilities, optional items, service support, software upgrade support, hardware upgrade support and the corresponding costs of each of these items. It is also useful to obtain a list of institutions and contact persons of users of the specific system in question. Based on the responses the department can then proceed to rank the systems available on the market in terms of their ability to satisfy the department's needs within its budgetary constraints.

At this time the vendor should be required to supply a draft acceptance test of the TPS. Some vendors require that measured data from the available treatment machines be sent to the factory for data entry and parameterization. The vendor should be required to state the time needed for the delivery of commissioning data.

7.3. VENDOR DEMONSTRATIONS, PRESENTATIONS AND SITE VISITS

The three or four vendors that head the list should be invited to provide more detailed information about their system's ability to fulfil the department's needs. This is best done by asking them to make a treatment planning computer available to the department on a temporary basis, or, if this is not possible, to host the department's physicist, dosimetrist or treatment planner at their own facilities. In either case, the main purpose is to let the staff of the purchasing department have some direct experience with the system. The user should attempt to get as much hands-on experience as possible to get a feel for the user interface as well as a real understanding of how the system works. Indeed, it is useful to take representative common clinical cases and to perform the calculations to see how the system is able to handle both routine and some unusual techniques. Examples here include standard techniques such as breast, lung and pelvic (prostate, gynaecological, bladder) treatments, head and neck cases, Hodgkin's disease mantle fields, possibly at extended distances, the use of electrons and other techniques in common use. Any special technique likely to be used should be evaluated. Furthermore, the data entry user interface should

be evaluated, since this is a part of the system that users often do not try until it is time to enter their first set of data.

During this time with the vendors, the department should explore the capabilities and limitations of the system, with particular attention paid to the adequacy of the user interface, the data entry process and the amount of data required for actual dose calculation commissioning. Some systems require much more in the way of measured data than others. In addition, it is important to learn about the vendors' timetable for software upgrades and their plans for improving the dose algorithm and to establish which features are under development and not yet fully functional. Vendors tend to understate times, and the buyer should be wary about promises if a desired feature is not yet available. It is important to obtain a written commitment from the vendor specifying the expected delivery dates. Finally, the department must use the opportunity offered by such a meeting with the vendor to assess the likely changes in departmental procedures necessary due to the purchase of the vendor's system. Two cases in point are the MU/time calculation process and the treatment plan normalization process. In addition to vendor demonstrations, the purchaser should also visit or make direct contact with individuals in clinics that work with the specific systems of interest, to see them in clinical operation, in addition to obtaining a personal assessment from these users.

7.4. TENDER PROCESS: DEFINITIONS OF SYSTEM SPECIFICATIONS

Once the department understands the technical specifications and approximate cost of each system, it is ready to develop a detailed tender document specifically requesting vendors to detail specifications, service issues, warranties, software upgrade contracts, hardware upgrade contracts, options and pricing.

The following is a sample table of contents of a TPS specification document used for tendering for a multistation TPS. This has been adapted from the TPS tender document produced at the Ontario Cancer Institute–Princess Margaret Hospital in 1994 [25].

(a) Document objectives.
(b) Definitions:
    (i) Base 3-D unit;
    (ii) Standalone server node;
    (iii) Remote 3-D node;
    (iv) Remote 2-D node;

(v) Remote MU calculation node;
(vi) Remote 3-D volume delineation node.

(c) Summary of essential requirements.

(d) Regulations, codes and standards.

(e) Vendor guarantees:
(i) Specification guarantee;
(ii) Service guarantee;
(iii) Third party products;
(iv) Performance guarantee;
(v) Computer protection;
(vi) Upgradeability;
(vii) Indemnity;
(viii) Price guarantee.

(f) Vendor information:
(i) Vendor statistics;
(ii) Model statistics;
(iii) Future capabilities.

(g) Purchase procedure:
(i) Site preparation;
(ii) Delivery;
(iii) Installation;
(iv) Acceptance testing.

(h) Payment terms.

(i) Specifications:
(i) Hardware;
(ii) System administration software;
(iii) Network and interface software;
(iv) Planning software;
(v) Documentation and training;
(vi) Servicing and parts;
(vii) Environmental requirements:
- Power;
- Operating conditions.

(j) Other information.

The tendering process has several advantages: (1) it forces the user to think about and organize the required specifications; (2) it forces the vendor to give specific answers about system capabilities and limitations; (3) it provides a legally binding contract; and (4) since it goes to various vendors, it provides a recognition by the vendors that they are in competition with others and that therefore they will need to quote competitive prices.

The tender document protects the department against a vendor's tendency to understate the price and reduces the possibility that the vendor, once chosen, will fail to meet the department's specifications. It should therefore be a carefully considered document.

7.5. SELECTION CRITERIA

Before submitting the tender document to the vendors, a set of selection criteria should be developed. Firstly, the department should make a list of those items that are essential, important but not essential, useful, and not needed. The list should also include any optional items the department might be willing to consider. A typical example of such a list is given in Table 22.

It is important to recognize that no system is perfect. Consequently the department should rank the importance to its operations of such subjective factors as the quality of the coding, the quality of the user interface, the ease with which radiation data can be entered and the stability of system operations.

7.6. PURCHASE

Before committing to the leading contender, the department ought to return to that vendor for additional discussions concerning the configuration of the system to be purchased and the final price of such a system. At this stage it may be possible to negotiate additional items or options.

This is also the time to negotiate hardware and software maintenance contracts and prices. It is important to check whether software upgrades will be provided in the cost of the contract, thus making internal budgeting more predictable. Although the same advantages apply for hardware upgrade programmes, few vendors offer this. Since hardware changes quite rapidly, vendors tend to be cautious about committing themselves to long term contracts at a fixed price. The purchase contract should include hardware and software specifications and the requirements concerning specific training, content of the documentation, assurance of the compatibility (conformance) of files transferred from the imaging devices (CT, MRI, etc.) and TPS data transferred to other devices (simulator, computerized block cutter, etc.). The acceptance test protocol must be part of the purchase order so that both sides agree as to what constitutes acceptance of the TPS and both sides are aware of the expectations of the other party.

TABLE 22. SAMPLE SELECTION CRITERIA AND EXAMPLE RANKINGS

(Concept adapted from a similar table produced at the Princess Margaret Hospital, Toronto, Canada; adapted, with permission, from Ref. [25].)

Item	Essential	Important but not essential	Useful	Not needed
Input–output				
Patient data				
Digitizer	Yes			
Film scanner	Yes			
Laser camera		Yes		
Plotter (vector)				Yes
Printer (black and white laser)			Yes	
Printer (colour)	Yes			
Network	Yes			
Keyboard	Yes			
Image transfer				
Floppy				Yes
Magnetic tape			Yes	
Cartridge			Yes	
Network				Yes
Optical disk			Yes	
CT scanner data (specify vendor)	Yes			
MR scanner data (specify vendor)	Yes			
Simulator images (specify vendor)		Yes		
Portal images (specify vendor)		Yes		
User interface				
Mouse	Yes			
Keyboard	Yes			
Interface customizable		Yes		

7.7. VENDOR AND USER RESPONSIBILITIES

7.7.1. Vendor responsibilities

The vendor has specific responsibilities to the user regarding the TPS. These should include the following:

(a) Accurate specifications outlining system capabilities.

(b) A summary of published references to algorithms and their capabilities and limitations. Reference [71] specifies that for each algorithm used, the accompanying documentation shall state the accuracy of the algorithm relative to measured data for at least one set of predefined conditions.
(c) Detailed system documentation, including the overall system design, the theory of the calculation algorithms, the algorithm capabilities and limitations, and a detailed users' guide indicating what the system does at each stage of the planning process. A clear description of dose normalization and MU calculations, for example, should be included.
(d) User training, including: (1) basic training of the use of the TPS; (2) details of the required measurements and the system commissioning process; (3) system management training; (4) more sophisticated applications training related to complex planning; and (5) implementation of a QA programme.
(e) Detailed information regarding software updates, including specifics about program alterations and enhancements.
(f) Clear communication with users regarding bugs or error reporting, errors found and potential remediation.
(g) Timely technical support.
(h) While total protection against unauthorized access via the network is difficult to implement, the vendor should take steps to minimize this possibility. The vendor should inform the user about the method to be used as a precaution [71].

While currently not available from most vendors, it would be extremely useful if vendors were to develop automated QA tools that would guide the system through a series of procedures and automatically assess whether these procedures are within the system specifications. This is especially useful for software updates, but also assesses whether any data files were inadvertently changed.

7.7.2. User responsibilities

The following summarizes the user's responsibilities:

(a) Definition of a responsible physicist to supervise and manage all aspects of the TPS installation, acceptance, commissioning and QA process.
(b) Implementation of the acceptance, commissioning and QA process.
(c) Detailed record keeping associated with the acceptance, commissioning and QA process.
(d) User training related to all practical aspects of the clinical use of the TPS.

(e) Staff education of all those who use the output from the TPS. This includes training of the radiation oncologists, radiation therapists and other staff who may not have hands-on use of the system but who will need to understand and interpret the output of clinical treatment plans. This includes education at the first clinical implementation of the TPS and also regular in-service reviews.
(f) Implementation, commissioning and QA of software upgrades, including detailed documentation.
(g) Ongoing communication with the vendor regarding software bugs and remediation.
(h) Ongoing communication with the users of the output of the TPS, such as radiation oncologists and radiation therapists, regarding system limitations and bugs.

8. ACCEPTANCE TESTING

8.1. INTRODUCTION

Acceptance testing is a process designed to verify that the TPS behaves according to specifications, either those outlined in the user's tender document, if such a document exists, or those defined by the manufacturer. Acceptance testing should be carried out before the system is used clinically and must test both the basic hardware and the system software functionality. Since during the short acceptance period the user can test only basic functionality, he or she may choose a conditional acceptance and indicate in the acceptance document that the final acceptance testing will be completed as part of the commissioning process. Besides testing the TPS, an additional benefit of this acceptance testing process is that it educates the user on many aspects of the TPS.

The acceptance test procedures to be used must be agreed upon by both the user and the vendor and must be clearly recorded. A procedure document should be written that describes the individual procedures in detail. All tests must be passed and any deficiencies should be clearly stated in the acceptance document.

Results of the acceptance tests should be carefully documented and kept as long as the TPS is used in the department, as they could be used for reference in future upgrades of the system.

The ongoing QA programme that will be implemented by the user should be based on the functional performance of the equipment at the time of the acceptance testing and commissioning of the equipment for clinical use [31].

The following summarizes the various components of the acceptance testing of a TPS. The intent of the following information is not to provide a complete list of items that should be verified but rather to suggest the types of issue that should be considered.

8.2. HARDWARE

A practical approach to acceptance testing is first to test the system's hardware.

The hardware test ensures that both the computer and its peripherals are operating in accordance with the specifications. The following devices should be checked for functionality and accuracy:

(a) CPUs, memory and disk operation. Most computers have system diagnostics that test CPUs, memory and disk operation. Commercial packages are available to perform CPU, memory and disk drive exercising tests.
(b) Input devices:
    (i) Digitizer tablet: check for linearity.
    (ii) Film digitizer: check transfer.
    (iii) Imaging data (CT, MRI, ultrasound, etc.): check input interface.
    (iv) Simulator control systems or virtual simulation workstation: check transfer.
    (v) Keyboard and mouse entry: check functionality.
(c) Output:
    (i) Hard copy output (plotter and/or printer): check for accuracy.
    (ii) Graphical display units that produce DRRs and treatment aids (custom blocks, MLC, etc.): check for functionality and absence of image distortion.
    (iii) Unit for archiving (magnetic media, optical disk, etc.): check for functionality.

8.3. NETWORK INTEGRATION

The TPS may be part of an integrated, networked imaging and data environment within the radiotherapy department. CT is the primary imaging

modality for treatment planning, and MRI, nuclear medicine scans and ultrasound may also be used. In addition, data may be exported from the TPS to patient management or record and verify systems, block cutting devices, etc. Checking network connectivity is part of acceptance testing.

Most scanning devices today can be equipped with a standard DICOM communications port that allows images to be transferred to the TPS following a standard protocol.

Although DICOM-3 is the current standard, there is still some lack of correspondence between the various DICOM implementations released by different manufacturers. The new standard DICOM-RT includes a vast array of options. However, the TPS may not support these options, or they may need to be specifically purchased. Interconnection of the TPS and other systems is possible when both ends of the link have a common implementation of a communication protocol, be it DICOM, FTP (file transfer protocol), a proprietary protocol or another standard.

8.4. DATA TRANSFER

As part of the acceptance process it is important to assess file compatibility and to test the following items (wherever appropriate):

(a) Network traffic and the transfer of CT, MRI or ultrasound image data to the TPS.
(b) CT data accuracy.
(c) Positioning and dosimetric parameters communicated to the treatment machine or to its record and verify system.
(d) Transfer of information to the MLC prescription preparation system for conversion of a planned MLC field to the leaf co-ordinate position.
(e) Transfer of DRR information.
(f) Data transfer from the TPS to auxiliary devices (i.e. computer controlled block cutters and compensator machining devices).
(g) Data transfer between the TPS and the simulator or virtual simulator, and digitized image information sent to or received from the simulator.
(h) Data transfer to the radiation oncology management system.
(i) Data transfer of measured data from a 3-D water phantom system using network connections or magnetic media. Check that file formats are compatible with the TPS.

8.5. SOFTWARE

8.5.1. Verifying system capabilities

The user can usually test only basic software functionality in the time available. The acceptance testing programme should check that all software features that have been purchased are actually installed and functional. TG 53 [18] includes guidelines on what to test. Table 23 is adapted from TG 53.

TABLE 23. ACCEPTANCE TEST FEATURES
(Adapted, with permission, from Ref. [18].)

Topic	Test
CT input	Create an anatomical description based on a standard set of CT scans provided by the vendor, in the format to be employed by the user.
Anatomical description	Create a patient model based on the standard CT data discussed above. Contour the external surface, internal anatomy, etc. Create 3-D objects and display.
Beam description	Verify that all beam technique functions work, using a standard beam description provided by the vendor.
Photon beam dose calculations	Perform dose calculations for a standard photon beam data set. Tests should include various open fields, different SSDs, blocked fields, MLC shaped fields, inhomogeneity test cases, multibeam plans, asymmetric jaw fields, wedged fields and others.
Electron beam dose calculations	Perform a set of dose calculations for a standard electron beam data set. Include open fields, different SSDs, shaped fields, inhomogeneity test cases, surface irregularity test cases and others.
Brachytherapy dose calculations	Perform dose calculations for single sources of each type, as well as several multisource implant calculations, including standard implant techniques such as a gynaecological insertion with tandem and ovoids, two plane breast implant, etc.
Dose display, DVHs	Display dose calculation results. Use a standard dose distribution provided by the vendor to verify that the DVH code works as described. User created dose distributions may also be used for additional tests.
Hard copy output	Print out all hard copy documentation for a given series of plans, and confirm that all textual and graphical information is output correctly.

8.5.2. Verifying calculation capabilities

Software tests should be performed in order to assess the performance of the dose calculation component of the system relative to criteria of acceptance, accuracy and functionality. The beam parameters and basic radiation data necessary in the testing process can be taken from published benchmark data, from generic data provided by the vendor of the TPS or from data measured on the centre's own machine. Generic data are a general data set for a particular accelerator or cobalt machine, but not the user's specific machine. Such generic data may be relevant to users of ^{60}Co machines, assuming that the model and source size are identical, although verification testing is still required.

As linear accelerators become more stable and consistent, there is a trend for manufacturers to supply a set of so called gold reference data along with the machine. These data are supposed to be representative of the machine delivered to the clinic, and during the installation efforts are made to match the beam characteristics to them, within some stated tolerances. Furthermore, if the machine manufacturer is also the vendor of the TPS, the vendor can prepare the TPS beam library to be directly compatible with these gold reference data. Such data can be used as generic data for assessing the basic capabilities of the algorithm, but it is currently recommended that all individual users use their own dose measurements and beam parameterization for commissioning purposes (see Section 9.2).

8.5.2.1. Calculation on benchmark data

Purpose:

(a) To test basic calculation capabilities;
(b) To detect errors due to the computer algorithm;
(c) To check the accuracy of the computer algorithm.

Procedure: Benchmark data from Ref. [72] can be used for algorithm assessment. The benchmark contains measured data for the photon beams of two machines (4 MV and 18 MV linear accelerators) and the results of a series of tests. The tests include a selection of standard fields (central plane and off-centre plane, oblique incidence, an irregular L shaped field and an inhomogeneous medium).

A set of data was recently measured that includes the extra functionality offered by modern therapy machines [73]. The test set includes missing tissue geometry and asymmetric collimator and MLC settings.

The National Cancer Institute Electron Collaborative Work Group (ECWG) [74] electron data set could be used for a series of verification checks of the accuracy of the system's 3-D electron pencil beam dose calculation.

8.5.2.2. Calculation on generic data

Purpose:

(a) To check the overall software implementation on the user's hardware;
(b) To test the basic calculation capabilities.

Procedure: Beam data provided by the vendor (or by others), so called generic dose distribution data, are useful for checks of software self-consistency. The user can verify the correct functioning of the system. The vendor should provide the expected test results. These include results of dose calculations and the appearance of graphic displays and hard copies.

Generic data should never be used for dose calculation verification testing. Only data that have been measured on the specific treatment machine being commissioned into the TPS should be used.

8.5.2.3. Calculation on the institution's data

Purpose:

(a) To check whether the measured beam data have been correctly implemented into the TPS;
(b) To test the basic calculation capabilities.

Procedure: A comprehensive evaluation is difficult to perform in the brief period generally allowed for acceptance. Measurement of the physical data for the centre's own machines and all the photon and electron energies available in the department will be done during the commissioning and could take several weeks or months. However, it may be possible to conduct basic tests using a limited set of measured data.

8.5.3. Utility software checks

The basic utility of the following software should be tested:

(a) Archiving software for storing non-current patient data.
(b) Backup software for the patient database.

(c) Printing or plotting software for producing isodose distributions.
(d) Software for entering measured absorbed dose data and parameters of the treatment unit. Check that the geometry of the data acquisition measurement set-up and 3-D co-ordinate system of the computer controlled water phantom are correctly understood by the TPS software.
(e) Software for entering brachytherapy radioisotope data.
(f) Software for accessing and printing dosimetry data and the treatment unit and source data.
(g) If a check sum or other security checks on the executable files and beam data files have been supplied, test them for correct implementation.

8.6. DOCUMENTATION

Extensive documentation on how the TPS software works should be available, including a description of the overall design, the theory of calculation, the limitations and detailed information on what happens as each step of the planning process is performed.

The data associated with treatment machine beams, brachytherapy sources and other parameters required by the system should be available to the user even before purchase of the system.

Reference [71] specifies the documents to be provided by the vendor (manufacturer) as part of the technical description and instructions for use:

(a) The vendor (manufacturer) should supply descriptions of the algorithm used in its systems and provide the accuracy of that algorithm.
(b) The vendor should provide information on the hardware and software QA programme that is used to design, develop, test, document and release the software.
(c) The vendor should release detailed descriptions of the datafile formats and contents that have been used for data import and export, along with examples of the correct implementation of the data transfer mechanism. Whenever possible, generally accepted protocols should be used.

A part of acceptance testing is checking that all the documentation has been supplied.

9. COMMISSIONING

9.1. INTRODUCTION

Commissioning is one of the most important parts of the entire QA programme for both the TPS and the planning process. Commissioning involves testing of system functions, documentation of the different capabilities and verification of the ability of the dose calculation algorithms to reproduce measured dose calculations.

9.1.1. Purpose

The purpose of the commissioning process is to enhance the QA of the TPS and planning process in a number of ways:

(a) Performing the various treatment planning tests provides experience and training for the users of the TPS;
(b) The tests of calculations give an indication of the capabilities and limitations of the dose calculation and other algorithms;
(c) The different tests provide documentation of the capabilities and performance of the system;
(d) Properly defined test scripts can give users an indication of the overall capabilities of the system over the clinical range of practice within the clinic;
(e) Some of the commissioning tests can subsequently be used as references for QC tests.

This section describes in detail many of the different tests and procedures that will aid users in defining their commissioning procedures.

9.1.2. General documentation guidelines

Appropriate documentation of QA testing and other aspects of a QA programme are an important part of the overall QA process. While specific legal requirements for documentation may vary widely among countries, this report suggests general types of documentation that are appropriate to keep for medicolegal and other reasons.

Throughout this report specific recommendations for types of documentation to be generated and saved are made. A number of general recommendations are listed below:

(a) Paper or computerized files may be used as documentation; however, the same basic requirements for content are used for each type of document.
(b) All documents should be dated. All documents that are part of an approval process (e.g. leading to the clinical release of a TPS) should include both the date and the signature (or computerized equivalent) of the persons giving the approval.
(c) Modifications of all documents should include the date of modification, the responsible individuals and a summary of the purposes of the modifications.
(d) Calculation verification tests, summaries and other data intensive documentation should include enough detail in the report that the source of the data, calculations and other important aspects of the report can be identified.
(e) Complete documentation (hard copy or electronic record) of all TPS system parameters that govern the operation of the system (including dose calculations) should be maintained. Copies should be stored in a location separate from the TPS.
(f) Data used for TPS input, calculation checks and other uses should be carefully documented, including a description of the set-up and information on detector types, the measurement and analysis techniques used, the people responsible for the measurements, the date and other relevant parameters.
(g) Important computerized or paper files that contain the QA documentation should be secure from inappropriate modification or removal.

9.1.3. General organization

The general organization of this section on commissioning is modelled after the treatment planning process (Section 2). For each part of this process, this report describes some of the more important QA aspects and describes tests and other activities that may be useful to the user in commissioning the TPS. The section organization is listed in Table 24.

9.1.4. How to use Section 9

Section 9 contains tests and procedures for a very wide range of TPS capabilities and sophistication. To help the user understand how to use this section, we will use the basic planning capabilities listed in Table 25 to show how one should choose the tests that should be performed at a particular institution. Table 25 lists the TPS capabilities to be tested, and in each of the parts of Section 9 a table listing the subset of tests that are relevant to that capability

TABLE 24. ORGANIZATION OF SECTION 9

Section	Topic	Description
9.1	Introduction	Introduction to methodology, organization, etc.
9.2	TPS system set-up	Set-up of TPS system parameters and machine and source configurations
9.3	Patient anatomy	Acquisition of patient data, transfer of data into the TPS and checks of the patient anatomical model
9.4	External beam commissioning	Definition of external beam technique, dose calculations and MU calculation and plan normalization issues
9.5	Brachytherapy commissioning	Definition of brachytherapy sources, dose calculations and absolute and relative dose issues
9.6	Plan evaluation	DVHs, dose displays, plan normalization and biological effect models
9.7	Plan output and transfer	Hard copy and electronic plan data output
9.8	Overall clinical tests	Typical plan examples (external beam and brachytherapy) carried through the entire planning process

(Table 25) is given. For an institution with only basic planning capabilities, only the subset of levels listed in the example tables would need to be performed. For different types of planning capability at a particular institution, a different subset of tests should be performed.

In addition, the reader can find in the Appendix tables intended to summarize the tests that should be performed during the commissioning phase. These tables are useful as checklists to make sure that all items have been surveyed to prevent any abnormality, but also, and probably more importantly, to acquire a sound understanding of the software characteristics. The tables have been divided into 'basic' and 'full' tests, where the full tests are linked with CT based and/or 3-D conformal planning capabilities.

9.2. SYSTEM SET-UP AND MACHINE–SOURCE CONFIGURATION

Most TPSs require many decisions to be made by the user during the installation process, and the user often has the possibility of choosing between different options or preferences that determine how the TPS will perform. This decision making is often referred to as customization or configuration.

TABLE 25. EXAMPLE OF BASIC PLANNING CAPABILITIES
(This list of basic capabilities is defined (for the purposes of this report) to show the types of test that need to be performed for this level of basic treatment planning.)

Subject	Capability
Patient anatomy	Manual contours ±CT input
Field size and shaping	Collimator jaws Blocks (and trays)
Beam set-up	Isocentric and SSD set-up treatment technique Gantry and collimator angle rotations, but no table angle rotations
Accessories	Wedges (hard)
Beam display	Axial planes (only) allowed for planning
BEV	No BEV
Inhomogeneity corrections	Bulk density corrections are used
Plan evaluation	2-D isodose lines
Documentation and plan transfer	Hard copy output No electronic transfer
Brachytherapy	Manually loaded implant Automated loading (HDR or low dose rate (LDR) for gynaecological applications)

The range and type of options varies extensively between the different TPSs. Table 26 lists the various broad categories of system set-up issues, customizable features and configuration questions. Some details of each of these items are then described.

9.2.1. General comments

Many of the customization and configuration decisions for the TPS are made during the installation and acceptance procedures. As part of the commissioning process, however, the user should reconsider the full list of decisions and options that were defined, keeping in mind the planned clinical use of the system. A list of the various decisions made, and of the possible options, should be documented, and the user should investigate the implications of these decisions. It is possible that any parameter or decision could dramatically affect the behaviour of large segments of the TPS, and changing

TABLE 26. TREATMENT PLANNING SYSTEM SET-UP, CUSTOMIZATION AND CONFIGURATION

Subject	Section	Description
General issues	9.2.1	Comments that apply to all system set-up issues
Computer hardware	9.2.2	Computer hardware configuration, peripherals such as printers and plotters, connections with external devices such as digitizers and the CT scanner
Computer software	9.2.3	Location of files, executables, logical symbols, log files, command files, patient data files, system configuration files, machine database files, etc.
TPS configuration	9.2.4	Selection of accessible functions, selection of algorithms and TPS co-ordinate systems
Patient database	9.2.5	Layout and fields to be included in the patient database, and archive methods and location
TPS data exchange	9.2.6	Formats (filters) for data exchanges, both for import and export
Display configuration	9.2.7	Layout of screen display and printout
Planning protocols	9.2.8	Protocol related information such as list of structures, predefined beam arrangement, list of isodose values, etc.
CT conversions	9.2.9	CT number to relative electron density
Machine database	9.2.10	Machine, beams, wedges, etc.
Source library	9.2.11	Source definition, library for sources, etc.
Dose calculation algorithms	9.2.12	Parameterization of algorithms: basic algorithm configuration and machine–beam parameters

such a parameter could conceivably invalidate a large amount of commissioning and QA testing. No parameters or configuration decisions should be changed without consideration (and knowledge) of the implications of the change, followed by retesting of the relevant issues.

9.2.2. Computer hardware

The computer hardware used for a modern TPS can range from a simple single workstation system with a printer and digitizer to a distributed multi-workstation or clustered system with complex network connections and numerous peripherals. The configuration of the entire TPS, including details of

the hardware set-up of the system, is determined using various system parameters. Documentation of the system set-up is critical. Understanding the implications of changes to any of these parameters is even more essential so that the user does not inappropriately modify some aspect of the system that is critical to system behaviour.

9.2.3. Computer software

As with the set-up of the TPS hardware, software configuration of the system is also crucial. Often this is a combination of operating system parameters (file locations, logical symbols, command files) as well as TPS configuration information. Often, many of these parameters depend on details of the user's system or on how that system will be used. The set-up, maintenance and documentation of the software configuration are therefore essential for correct system operation. Appropriate QA procedures for system maintenance also include maintaining security for the software and its configuration, appropriate backups (in case of hardware failure) and other tasks discussed further in Section 10.

9.2.4. Treatment planning system configuration

Configuration of the TPS system often includes definition of which TPS functions are going to be accessible to the user, as well as which types of calculation algorithm will be available. The definition of algorithm accessibility is critical, since use of an algorithm before it is fully prepared and released for clinical use could be dangerous.

Each TPS has additional objects, relationships and co-ordinate systems that are inherent in the system design, which can have a significant influence on how the TPS is used and on how the output from the TPS should be interpreted. The user of the system must learn enough about these internal issues to understand the manner in which the system works. Internal co-ordinate systems are a good example: in a TPS there are numerous co-ordinate systems, describing CT scans and other imaging data sets, anatomy, the patient on the treatment table, the beam in the gantry, etc. To really understand how these different systems interact, the TPS documentation and vendor instructions must be studied, and various tests performed to confirm the understanding. This kind of study and experimentation can help the user avoid misuse of the TPS. Examples of different co-ordinate systems include those defined by the International Electrotechnical Commission (IEC) [75] and the ICRU [37].

9.2.5. Patient database

An important aspect of any clinical software system is the patient database and the demographic information contained in it. The patient related information that may be contained in the TPS patient database is different for each TPS, and many TPS databases can be configured in different ways in order to match the information that is required or desired by the institution. In addition, it is often necessary to obtain data from or pass data to the hospital information system's databases. Finally, patient data from the TPS must be archived when the patient has completed therapy, and details of the location of the archive of this information must be stored, in order to make later retrieval of the archived data possible. For all of these issues, careful layout of the database, archiving methods, database use and connections to other systems must be confirmed after system installation and set-up, and after upgrades. Careful maintenance of the patient database and the methods used with that database should be part of any TPS QA programme.

9.2.6. Treatment planning system data exchange

Data exchange into the TPS or out of the TPS must be carefully configured and tested. One of the most obvious examples is the use of CT images, and tests of this capability are described in Section 9.3. However, any transfer of data in or out should also be carefully set up, documented and tested. This can include input of water phantom scan data, transfer of plan information into a record and verify system to assist with treatment delivery, or any other kind of electronic data exchange. Each such exchange must be commissioned with formal testing and rules for how the exchange should be performed.

9.2.7. Display configuration

In some TPSs it is possible to modify the graphical display and/or hard copy output formats. Since these two display media communicate much of the treatment planning information to the user, how the information is displayed can be crucial to how users interpret and use the planning data. The information format is often determined at system installation, and should be reconfigured only with planning by the user on how the new information format will be used.

9.2.8. Planning protocols

How different cases will be planned is an important aspect of the QA for the entire planning process. Each institution can help create a more robust treatment planning process by defining specific planning protocols: how to use the TPS, how to make decisions during the planning process and how to plan specific cases. The use of planning protocols differs in different TPSs, and may include the creation of standard 3-D structure definitions, predefined beam arrangements, standard sets of isodose curve values that are plotted, as well as procedural methods. All these details must be confirmed if the usefulness of the planning protocol for improved planning QA is to be realized.

9.2.9. Computed tomography conversions

Since megavoltage photons interact with tissue primarily through Compton interactions, dose calculations for patients require the use of relative electron densities. One of the most important advantages of CT scan technology is that one can obtain the relative electron density for tissues of interest from the scan information. Typically, CT numbers are defined in Hounsfield units (HU) by the following equation:

$$\text{CT number} = 1000\left(\frac{\mu - \mu_w}{\mu_w}\right) \tag{8}$$

where μ is the attenuation coefficient of the voxel of interest and μ_w is the attenuation coefficient for water. It is possible that some scanners use a different scaling factor or have an offset in the CT numbers as they are stored in the image files. While this is generally no longer the case, it is still important for the user to ensure that the CT numbers, as fed into the TPS, are understood properly and that there are no calibration offsets. While CT scanners are generally calibrated with air and water values, the conversion of CT numbers to relative electron density values is dependent on the atomic number of the tissue. The conversion from CT numbers to relative electron density is given by published data [76–78]. This conversion depends on the particular scanner (particularly its calibration and software). If multiple CT scanners are used with the TPS, then the specific conversion methods must be configured correctly for each scanner. Commissioning and QA tests for these conversions are described in Sections 9.3 and 10. Other similar conversions, from CT numbers to electron linear stopping power and electron angular scattering power, are also used [46, 79].

9.2.10. Machine database

One important aspect of the configuration of a TPS is the creation of a machine database that contains descriptions of the treatment machines, beams, wedges, beam modifiers and other aspects of the equipment that will be used to deliver the treatments.

Each TPS requires the entry of a set of parameters, names and other information, which is used to create the geometrical and mechanical descriptions of the treatment machines for which treatment planning will be performed. These parameters constitute the core of the treatment machine database (or library) and also contain links to the parameters or dosimetric data that are used within the dose calculation modules. The following are examples of machine parameters:

(a) Identification (code name) of machines, modalities, beams (energies) and accessories.
(b) Geometrical distances: SAD, collimator, accessory, etc.
(c) Allowed mechanical movements and limitations: jaw limits, asymmetry, MLC, table, etc.
(d) Display co-ordinate system (including gantry, collimator and table angles, table x, y, z position, etc.).

In principle, non-dosimetric parameters (such as those listed above) do not require measurement, and are typically obtained directly from treatment machine documentation. However, issues such as co-ordinates, names and device codes require verification, since any mislabelling or incorrect values could cause systematic misuse of all the plans generated within the TPS.

Configuration parameters must be organized and entered in a sensible and consistent manner so as to facilitate safe clinical use of the system; for example, the choice of machine and beam names, device codes and other such parameters is critical for safe and error free use of the TPS.

At the completion of the commissioning process the user must ensure that any machine, modality, energy or accessory that has not been tested and accepted be removed, made unusable or otherwise made inaccessible to the routine clinical users of the system.

The tests of machine database parameters are described in Section 9.4.2.

9.2.11. Source data for brachytherapy

The definition of the brachytherapy sources to be supported, the creation and maintenance of the source library, and many other details required for

brachytherapy dose calculations are set by specific parameters and other configuration components of the TPS. One must distinguish between the tables that contain the dosimetric characteristics of the source–radionuclide combinations and the inventory of the sources that are currently kept on hand in the institution.

The parameters used for dose computation consist of tables and/or coefficients, according to the dose calculation algorithm (Section 4.5). Accurate determination and internal consistency of these parameters is one of the most important aspects of the QA requirements for brachytherapy planning. In particular, the dose rate constants, radial functions and anisotropy functions, as well as the half-lives, must be carefully entered and checked, since these could cause huge errors if they are incorrect. Such data will be kept as long as the same type of source is being used. On the another hand, the source inventory, if required by the TPS, should be maintained according to the sources currently used for the clinical applications. For this inventory, it is essential to make sure that the strength of each source and the corresponding calibration date are correct and consistent as far as the choice of quantities and units for source strength specification is concerned. Further discussion of detailed tests for these types of issue is contained in the section on brachytherapy commissioning (Section 9.5).

9.2.12. Dose calculation algorithms

Typically, each dose calculation algorithm requires specific parameters to ensure accurate dose calculation. Some of these parameters are set when the system is first configured, while others are defined as part of the beam fitting process. Some algorithms may also depend directly on tabulated measured data.

Configuration of the calculation algorithm may include determination of the files, file structure, file locations and other information. These parameters can be a very important aspect of how the calculation algorithm works, and must be set correctly. The same is true, of course, of each one of the parameters that affects the dose calculation algorithm. Further information about calculation algorithm parameter tests is included in Sections 9.4 and 9.5.

Basic data measured for use in dose calculation algorithms can be used directly as input to the beam data library, or the data can be processed with software specifically designed to: (a) extract the quantities required by the dose calculation algorithm and/or (b) transfer them into the beam data library with the proper format. In both cases it is useful to acquire most of the dosimetric data with a computer controlled water phantom and to transmit them numerically to the TPS. However, it is essential that this procedure be kept

under full user control, since it is very important that the data used to generate the beam library represent the beams that will be used clinically. It also is important that the data be manipulated with smoothing (within experimental uncertainty) and other adjustments until a consistent data set is achieved. For all non-dosimetric and dosimetric parameters it should be stressed that any change in beam characteristics or accessories (and particularly replacement of the cobalt source or absolute recalibration) requires that all the relevant data be updated, followed by partial or full recommissioning of the relevant dose calculation procedures.

9.3. PATIENT ANATOMICAL REPRESENTATION

The next step in treatment planning is the creation of the anatomical model of the patient. This includes:

(a) Acquiring information about the patient's anatomical description (Section 9.3.1);
(b) Input and transfer of that information into the TPS (Section 9.3.2);
(c) Creating the anatomical model of the patient that will be used as the basis of the patient's treatment planning (Section 9.3.3).

9.3.1. Acquisition of patient information

The planning process begins with the acquisition of some patient information, usually based either on patient shape information obtained with mechanical patient contouring (often performed in the simulator with some radiographic films) or with imaging data sets (CT most often, but also including MR, ultrasound and other modalities). This section (Table 27) describes some of the procedural issues that should be defined for the process used for patient data acquisition.

TABLE 27. ACQUISITION OF ANATOMICAL INFORMATION

Clinical issue	Description	Test	Required?
Contour acquisition	Direct patient contour acquisition: documentation and technique	Acquisition test 1	If used
CT	CT scan process	Acquisition test 2	If CT used

9.3.1.1. Acquisition test 1: Manual contour acquisition

Purpose: Documentation of the method used for the acquisition of manual (mechanical) contours.

Procedure:

(a) Define the standard process used to obtain multiple manual contours (at different z levels along the patient).
(b) Perform the contouring process for several different contours.
(c) Confirm that the following information is clearly documented on each contour: patient identification (ID), location of the contour, z value of the contour (relative to a defined reference point on the patient), left–right orientation, scale of the manual contour plot, identification of localizing marks (field centres, etc.), date and time, person who performed the contour and check of anteroposterior (AP)–posteroanterior (PA) and lateral separations (to confirm the contour and scale) and other relevant information.

9.3.1.2. Acquisition test 2: Computed tomography data acquisition

Purpose: To check and document the process used to obtain CT (or other imaging) data.

Procedure: Review the procedure that will be followed for patient treatment planning CT (or other imaging) scans and confirm that the procedure addresses the issues listed in Table 28.

9.3.2. Entry or transfer of input anatomical data

Purpose: To assess the accuracy of the entry or transfer of input data. Table 29 summarizes the data entry or transfer procedures and points to the relevant tests.

9.3.2.1. Input test 1: Digitizer calibration

Purpose: To confirm the calibration and function of the digitizer.

Procedure: The calibration test procedure is dependent on the type of digitizer used. However, the basic procedure is to define one or more manual contour shapes (at least one rectangular type object and one complex curved contour) on an accurate piece of graph paper. Enter the contours into the TPS. Use the TPS analysis tools used to document that the individual points entered, and the contours (as a whole), are recorded accurately by the TPS. The

TABLE 28. ACQUISITION TEST 2: COMPUTED TOMOGRAPHY IMAGING PROCEDURE ISSUES

Issue	Method
Patient and scan ID	Need unique patient ID, scan ID, date, time, etc.
Choice of imaging protocol	Imaging protocol depends on the field of view, scan thickness and/or spacing needed, use of contrast, method used to handle patient respiration and other motion, patient orientation, etc.
Patient set-up	Patient positioning is crucial: use the immobilization device planned for the treatment
Location of the origin	The definition of the origin for the scanner co-ordinate system must be documented and must follow standard procedure: the origin is typically defined by orthogonal skin marks (or tattoos), which are used for laser set-up in the treatment room
Use of modifying devices	If bolus or other devices (which may modify the patient's contour or density) will be used for treatment, they should be included in the scan
Patient orientation	Patient head or foot first; prone or supine positioning must be documented to the CT scanner if appropriate information is to be available for transfer to the TPS

TABLE 29. ENTRY OR TRANSFER OF INPUT ANATOMICAL DATA

Issue	Description	Test	Required
Contour acquisition	Digitizer calibration	Input test 1	If used
	Manual contour entry	Input test 2	If used
CT	Basic geometry and orientation	Input test 3	If CT used[a]
	CT tools in the TPS	Input test 4	If used
Other imaging modalities	MRI, PET, SPECT, ultrasound, etc.	Input issue 1	If used
Other patient data	Name, registration number, etc.	Input issue 2	Yes

[a] If tests are done on the TPS, it is not necessary to perform all the above on the CT scanner before transfer; however, it is critical that CT tests be performed on the TPS. The exception is that the orientation tests (prone, supine, etc.) should be performed both on the scanner and on the TPS.

contours must be large enough to test the entire active area of the digitizer, and must include simple and complex shapes. Printing out the shape of the contours on the TPS plotter, on a 1:1 scale, can often allow a simple comparison check between the original and plotted contours. It should be noted that the technique used for the entry of digitizer information can affect the accuracy of the system and that tests should therefore be defined to confirm that individual users correctly use and enter information into the system.

9.3.2.2. Input test 2: Manual contour entry

Purpose: To test the accuracy of the method used to record the geometric data and other documentation collected during the procedure (patient name, left–right markings, laser alignment marks, etc.).

Procedure: The specific methods for testing are dependent on the devices used. Use the contours measured (acquisition test 1) on a rigid, well described phantom (e.g. a humanoid phantom) for which there are accurate geometric descriptions, so that the measurements can be compared directly with known data. Comparisons of the output (e.g. the contours drawn on paper after transfer from the contouring device) can also be confirmed with these simple checks. The user should also confirm that various standard markings are correctly placed. These include left–right, anterior–posterior and laser alignment marks, the SSD to the central axis, the z location (distance up–down the treatment table) of the contour and other such information.

9.3.2.3. Input test 3: Computed tomography data acquisition

Purpose: To verify that CT data are accurately acquired on the CT system, correctly transferred to the TPS and reproduced accurately by the TPS.

Procedure: Perform the following tests for CTs acquired in all scan orientations to be used for treatment planning, including:

(a) Supine: head first.
(b) Supine: feet first.
(c) Prone: head first.
(d) Prone: feet first.
(e) Other orientations.

Note that the transfer protocol and other details of image use are dependent on the CT scanner and manufacturer, as well as on how the TPS interprets the data from each scanner. The following tests must therefore be performed independently for each CT scanner and TPS.

(1) Select the standard CT imaging protocol: the protocol includes the slice number, slice thickness, reconstruction circle and patient orientation. Note that the CT scanner must be calibrated (routine CT QC), as these results are dependent on the CT scanner calibration (both geometry and grey level).
(2) Select a known solid or water phantom, including known inhomogeneities (e.g. 10 cm or more in length; internal structures are helpful). The minimum phantom is the solid or water phantom used for QC on CT by the manufacturer. Add external radio-opaque markers for orientation (left–right, head–foot and anterior–posterior) at known locations to define the orientation and slice location.
(3) Perform the imaging study.
(4) Transfer to the TPS.
(5) Perform the tests listed in Table 30 and analyse the results.
(6) Decide upon the acceptability of the results.

Note that if there is any problem in the acceptability of the results of this test on the TPS, then it is important to perform the tests both on the CT scanner and on the TPS to help determine the location of the problem.

9.3.2.4. Input test 4: Computed tomography tools in the treatment planning system

Purpose: To verify that CT data can be used accurately by the TPS. This test is a very specific procedure that can be used for the most basic type of CT scanning protocol. For other CT imaging protocols, and for other tomographic imaging systems, analogous scanning and test protocols and methodologies must be designed and performed. The same kind of issues addressed in input test 4 must be tested for each imaging modality.

Procedure: For all of the distinct imaging protocols and/or imaging devices to be used, perform imaging and determination of the real geometric description of the test phantoms (the same phantoms and images as used in input test 3).

(a) Transfer imaging data to the TPS using digital input (CD-ROM, network, etc.);
(b) Display CT data on the TPS;
(c) Perform the tests listed in Table 31;
(d) Summarize the results.

TABLE 30. INPUT TEST 3 (COMPUTED TOMOGRAPHY): METHODS AND SPECIFICATIONS

Issue	Method	Specification	Considerations	Test on CT console and/or TPS
Geometric accuracy and distortions	Use the software measuring tool to measure the height, width and other distances for known structures defined in the phantom	0.2 cm	This can be different for each field of view (CT protocol)	Confirm agreement of CT and TPS
Orientation	Use axial CT images to confirm the correct location of orientation markers (left–right, superior–inferior, anterior-posterior) (this must be performed for each type of CT protocol)	Yes or no	Dependent on the patient position defined in the CT console, must check for each protocol and position to be used	Confirm agreement of CT and TPS
Slice location	Confirm correct relative (z) position of slices	0.1 cm	For each CT protocol	TPS
CT gantry tilt	For tilted CT scans (CT gantry angle non-zero), confirm the orientation, alignment, scale and co-ordinates of individual images	Same as for axial CT slice checks	Full check as for normal axial CT scans	Confirm agreement of CT and TPS

Notes:

(1) The CT scanner must be calibrated (routine CT QC), as these results are dependent on the CT scanner calibration (both geometry and grey level).
(2) These checks are required for each independent setting of the imaging system and for each transfer format. Each protocol and format can have different problems.
(3) For unacceptable tests, further investigation and action is required by staff.

TABLE 31. INPUT TEST 4: COMPUTED TOMOGRAPHY TOOLS OF THE TREATMENT PLANNING SYSTEM

Issue	Method	Specification	Consideration
Patient and study ID	The transfer process must confirm the correct choice of patient and study for input	Yes or no	Incorrect imaging study ID and input can be a big problem
Image grey levels and densities	Compare the CT number and relative electron density in the TPS	20 HU	Include TPS conversions to understand the comparison; check at least water, air and a bone-like object; note that density conversion issues are discussed in detail in Section 9.2.9
Image reconstruction	Sagittal, coronal and oblique image reconstructions: check scale, orientation, labelling, co-ordinates and image grey levels	Same as for axial CT slice checks	Full check as for normal axial CT scans
2-D and 3-D display	Confirm the appropriate display of 2-D images and 3-D visualizations of multiple images, where appropriate	Visual checks	Visual checks of all relevant display methods

(4) The transfer protocol and other details of image use, including the CT number to relative electron density conversions, are dependent on the specific CT scanner, as well as on how the TPS interprets the data from each scanner. These tests must therefore be performed independently for each CT scanner and TPS.

9.3.2.5. Input issue 1: Other imaging modalities

Each imaging modality has its own particular issues that must be studied, as summarized in Table 32.

9.3.2.6. Input issue 2: Patient database

Patient identification and demographic information must be stored in the TPS database and should be accurately disseminated to all features of the TPS, including all hard copy output. Testing of these issues is completely dependent on the local circumstances, and it is the responsibility of the institution to assess and handle these issues (Table 33).

9.3.3. Anatomical model

The anatomical description of the patient is often based on the images described in Section 9.3.2, but all parts of the anatomical modelling used to create this description must be checked. The specifics of the anatomical description can vary greatly among TPSs, and the functionality used to create those anatomical descriptions also varies from system to system.

TABLE 32. IMAGING MODALITY ISSUES

	Issue	Testing required
MRI	Geometric distortions	Phantom with 3-D structures (so that out of plane distortions and non-linearities can be seen)
	Geometry self-consistency	Registration checks (to make sure that different scan orientations are geometrically registered with each other)
PET	Resolution	Resolution of scans generally is broad: must ensure that the TPS can handle the larger resolution of PET scans
	Geometric registration	Confirm the ability to register scans with base CT scans
SPECT	Resolution	Verify the ability to handle limited SPECT resolution
Ultrasound	Operator sensitivity	Training sets, procedure for scanning and scan analysis checks
	Geometric accuracy	Confirmation with CT data or other phantom tests

TABLE 33. PATIENT DATA ISSUES

	Issue
Patient name	Avoid name confusion Maintain patient confidentiality
Patient ID	Uniqueness Accuracy
Demographics	Security and confidentiality
Link with hospital information system	Confidentiality, security, accurate transfer of information and timeliness

The basic functions used to create the anatomical model of the patient are given in Table 34, and tests of the most important aspects of this functionality are described. Specific tests are given below.

Table 35 shows the reduced tests to be performed by a user of a TPS with only basic planning capabilities (Table 25).

9.3.3.1. Anatomy test 1: Representation of contours without imaging

Contours are obtained by using some physical (or electronic) method of tracing the shape of the patient and then entering these 2-D contours into the TPS. Most often, the contours are traced into the TPS using an electronic sonic digitizer tablet.

Purpose: To verify that contour data can be accurately input into and used by the TPS. This test is a very specific test procedure that can be used for most digitizer based contour entry. For other contour entry methods, an analogous test must be designed and performed. Note that this is a continuation of acquisition test 1 (Table 27) and input tests 1 and 2 (Table 29).

Procedure:

(a) Define the phantoms to be used.
(b) Obtain physical contours of the phantoms at various points longitudinally along the phantom.
(c) Use the available method to input the manual contours into the TPS.
(d) Create the basic treatment plan using the input contours.
(e) Print out a hard copy of contours, to scale.
(f) Compare the resulting contours and verify the accuracy of the contours. Check the measurements (AP and lateral separations across the

TABLE 34. FUNCTIONALITY USED FOR THE CREATION OF THE ANATOMICAL MODEL

	Level of functionality	Test
Contouring	Entering contours without imaging	Anatomy test 1
	Drawing CT based contours	Anatomy test 2
	Automatic contouring	Anatomy test 3
	Editing of contours	Anatomy test 4
3-D objects	Creating 3-D description based on axial contours	Anatomy test 5
	Cutting 3-D objects into contours	Anatomy test 6
	Expansion of 3-D objects	Anatomy test 7
3-D density description	Creating density description for manual contour case	Anatomy test 8
	Densities based on CT	Anatomy test 9
	Anatomical bolus	Anatomy test 10
	Editing of CT densities	Anatomy test 11
Points and lines	Defining points, lines and marks	Anatomy test 12
Image display and use	2-D image display	Anatomy test 13
	Display tools (window, level, etc.)	Anatomy test 14
	Image reconstruction	Anatomy test 15
	3-D display	Anatomy test 16
	Image manipulation	Anatomy test 17
	Measurement tools	Anatomy test 18
Co-ordinate systems	Basic co-ordinate system	Anatomy test 19
	3-D co-ordinate readout	Anatomy test 20
	Using multiple data sets–image fusion	Anatomy issue 1

Note: Users should check which levels of functionality will be used for each kind of clinical situation, and then tests pertaining to each level of functionality must be performed.

contours) used by the TPS to verify that the representation of contours by the TPS agrees with the output contours.

9.3.3.2. Anatomy test 2: Manual contouring from computed tomography

Purpose: To verify accurate CT contour drawing.
Procedure:

TABLE 35. BASIC PLANNING CAPABILITIES EXAMPLE: ANATOMICAL MODEL

	Level of functionality	Test
Contouring	1. Entering contours without imaging	Anatomy test 1
	2. Drawing CT based contours	Anatomy test 2
	3. Automatic contouring	Anatomy test 3
	4. Editing of contours	Anatomy test 4
3-D density description	1. Create density description for manual contour case	Anatomy test 8
	2. Densities based on CT	Anatomy test 9
Points and lines	1. Defining points, lines and marks	Anatomy test 12
Contours and image display and use	1. 2-D image display	Anatomy test 13
	2. Display tools (window, level, etc.)	Anatomy test 14
	3. Measurement tools	Anatomy test 18
Co-ordinate systems	1. Basic co-ordinate system	Anatomy test 19
	2. 3-D co-ordinate readout	Anatomy test 20

Note: It is recommended that these tests, where appropriate, be performed on the same set of phantom CT scans, so that many of the tests can be combined into activities performed on a single case. Phantoms (some of which are available commercially) designed specifically allow testing of many of these functions on a single phantom [15].

(a) Use CT scans of a phantom with known dimensions of external and internal contours of objects (e.g. a square plastic phantom with cork inhomogeneity or a phantom with point landmarks), or with patient CT scan data as long as appropriate checks of patient shape are performed.
(b) Draw an external contour for a test phantom on multiple slices.
(c) Confirm agreement with the measurements.
(d) Draw internal contours and confirm the location, shape, etc., with known results. For all structures, use an appropriate CT image window width and level.

Issues:

(1) Precise agreement between the contours and the images from which they were derived should be looked for.
(2) Agreement between the contours and the known dimensions of structures should be looked for.
(3) Be aware that image zoom functions might disrupt this agreement.

(4) There might be differences of one or more CT pixels in the contour locations relative to the CT data.
(5) Incorrectly set CT display parameters (window and level) can cause the user to draw contours that generate too large or too small volumes of a particular organ. This is the biggest issue when creating accurate external surface and lung contours.

9.3.3.3. Anatomy test 3: Automatic contouring

Purpose: To verify the appropriate contouring of automatic contouring of CT data.

Procedure:

(a) Use the same phantom as in the earlier tests with known dimensions of external and internal contours of objects (e.g. a square plastic phantom with cork inhomogeneity or a phantom with point landmarks), or with patient CT scan data as long as appropriate checks of patient shape are performed.
(b) Use the automatic contouring capability to generate an external contour for the test phantom on multiple slices, and confirm agreement with the measurements for each slice.
(c) Generate an internal contour and confirm location, shape, etc., with known results. Use an appropriate CT image window width and level for all structures. If the TPS allows automatic contouring with different image zoom values, this function should be tested for each of these situations.
(d) If results are outside specifications, then one might look for:
    (i) Differences of one or more CT pixels in contour locations relative to the CT data.
    (ii) An incorrectly set threshold (or gradient) value on the automated contour tracking software, which can cause offsets of the contours, resulting in too large or too small volumes of a particular organ. Users may have to define their own threshold values (for a given CT image type and given structure) to obtain the correct contours.

9.3.3.4. Anatomy test 4: Editing of contours

Purpose: To verify the accurate editing of contours.

Procedure:

(a) Edit a series of different types of contour (including external contours or inhomogeneity contours).
(b) Verify that the expected changes are taken into account and that the contour results are correct. These changes may affect the patient anatomy and/or the dose calculations, and hence the reader is referred to the photon and electron beam commissioning tests (Sections 9.4.3 and 9.4.4).

9.3.3.5. Anatomy test 5: Generating a three dimensional object description

In many TPSs the 3-D representation is implicitly created directly from the 2-D contours; however, other systems do make 3-D representations (like a 3-D surface mesh or a 3-D voxel based representation) from the axial contour data.

Purpose: To confirm appropriate 3-D object creation.
Procedure:

(a) Use a series of cases with axial contours having different shapes, etc.
(b) If necessary, create the 3-D objects.
(c) For each object, create sagittal and coronal contours cut from the 3-D object.
(d) Confirm agreement with the axial contours. Confirm the 3-D shape of each object.

Also, check the single mechanical contour case by creating a single axial contour, creating the 3-D object and then checking the sagittal and coronal contours of the external surface.

See also the calculation validity test (operational test 3, Section 9.4.5).

9.3.3.6. Anatomy test 6: Generating new contours (from surfaces or interpolation)

Purpose: To confirm that the capability (if available) to create contours by cutting them from the 3-D description of the object works correctly.
Procedure:

(a) Create contours on slices located between slices that have already been contoured (either by interpolating between the relevant contours or by cutting the contour from the 3-D surface obtained from the defined contours).
(b) Verify that the new contours are appropriate. If possible, extract sagittal and coronal contours from 3-D surfaces based on axial contours.

9.3.3.7. Anatomy test 7: Object expansion

Purpose: To document that object expansion works correctly in 3-D.
Procedure:

(a) Simple test: Draw oval shaped contours on at least three different slices (different shapes on each slice) to make a simple 3-D object. Expand the structure with a 2 cm margin. Cut contours from the expanded object onto slices to show comparison with the original contours (include sagittal and coronal contours if possible).
(b) More advanced test: Draw a more complex shape including wedge shaped contours, sharp corners, concave contours and sharp shape changes in the sagittal direction. Carry out the steps as in the simple test.

Issues:

(1) How does the expansion behave at corners?
(2) How does it behave for concave contours?
(3) Does it work in 3-D uniformly, for 2-D axial expansions (only) or in some other fashion?
(4) Test anisotropic margins (in x, y, z) if available.
(5) What happens when you run out of slices (at the top and bottom of the structure)?
(6) Does the expansion work correctly when slices are not of the same thickness or spacing?

9.3.3.8. Anatomy test 8: Creating densities for manual contours

Purpose: To check the creation of bulk density structures.
Procedure:

(a) Define a simple square phantom with lung-like and bone-like regions.
(b) Use the TPS system tools to confirm the densities of regions in the phantom.
(c) Perform a single beam dose calculation through the inhomogeneities to confirm that density differences are used. If the system allows the use of overlapping structures, check this by creating overlapping inhomogeneities, creating the density description and confirming that the behaviour of the density is correctly defined by the hierarchy of structure definitions (and densities).

9.3.3.9. Anatomy test 9: Creating densities from computed tomography

Purpose: To check CT derived densities. This generates reference data for the periodic CT density check (Section 10, QC test 6).

Procedure: Obtain a CT phantom with known materials (with known densities). Scan the phantom using the standard CT protocol for TPS scans and contour the inhomogeneities in the phantom. Use the TPS system tools to measure the densities within the TPS system, for each inhomogeneity. Confirm that the relative electron density to be used in density corrected dose calculations agrees with the expected values.

9.3.3.10. Anatomy test 10: Creating an anatomical bolus

Purpose: To check the capability to add bolus.
Procedure:

(a) Use the CT phantom scans obtained in anatomy test 9;
(b) Add bolus to the outside of the contours and verify that the correct shape and densities are present.

9.3.3.11. Anatomy test 11: Editing of CT densities

Purpose: To check the capability to edit CT densities.
Procedure:

(a) Use the CT phantom scans obtained in anatomy test 9;
(b) Contour the various inhomogeneities and replace the actual density with the unit density;
(c) Verify that the correct densities are present.

9.3.3.12. Anatomy test 12: Defining points, lines and marks

Purpose: To confirm the behaviour of lines, points, marks and other ancillary objects.

Procedure: Since these features have many system dependent characteristics, the user must design most of the test.

(a) For each object (including marks, lines, points, etc.), define the points necessary to create the object while pursuing a clinical-like planning case;
(b) Use other features of the TPS to confirm that the object is displayed correctly, whether it has the correct 3-D co-ordinates, etc.

Note that if these objects are tied to particular co-ordinate systems or data sets, the objects should move with that data set.

9.3.3.13. Anatomy test 13: Two dimensional image display

Purpose: To confirm the correct display of 2-D images.

Procedure: Use normal clinical cases, if available. Verify qualitatively the correct behaviour of the 2-D image display visually for all methods of display.

9.3.3.14. Anatomy test 14: Two dimensional image display tools

Purpose: To verify the correct functioning of display tools (window and level, zoom, pan, colours, etc.).

Procedure:

(a) Create and perform simple tests of display functionality; for example, for the window and level display grey scale image.
(b) Check that various window–level combinations result in the visualization of specific grey level combinations.

9.3.3.15. Anatomy test 15: Generating two dimensional reconstructed images

Purpose: To verify that correctly reconstructed images are obtained.

Procedure:

(a) Use a CT scan of a CT phantom with known internal structures;
(b) Create reconstructed images in sagittal, coronal and oblique cuts;
(c) Confirm by the use of multiplanar displays or other methods that the internal anatomy and external surface of each reconstructed image is geometrically correct;
(d) Visually confirm that the correct grey scale values are also found in the new images.

9.3.3.16. Anatomy test 16: Three dimensional display and associated tools

Purpose: To verify the correct functioning of 3-D display modes.
Procedure:

(a) Create an anatomical model in the TPS with a well constrained (i.e. easy to interpret in a 3-D display) description.
(b) Use this model to perform simple tests of display functionality; for example, create 3-D displays for all relevant structures (including drawn target volumes).
(c) For each display mode, confirm that the displays directly show correct combinations of 3-D perspective, images, structure graphics, etc.

9.3.3.17. Anatomy test 17: Tools for the manipulation of anatomical data

Purpose: To assess the capabilities and limitations of tools used for manipulating anatomical data. Typical tools include slice translation or copying, slice–image flip (left–right or up–down), diagonal flip, etc.
Procedure:

(a) For each manipulation tool available to change the patient's anatomical representation and/or images, document the software capabilities while understanding the limits on the data and images that result from these capabilities;
(b) Use patient data for each tool and perform the specific action;
(c) Verify that the results are correct, as well as how the co-ordinate systems are changed, if at all;
(d) After agreement, perform some action on the contours and/or images as before, and compare the data after manipulation with the original data.

Note that some functions will change the anatomical model and/or the results of any dose calculations: these issues should be investigated when moving or flipping images and for similar types of operation.

9.3.3.18. Anatomy test 18: Measurement tools

Purpose: To assess the capabilities and accuracy of measurement tools. Typical tools include the distance measure, circular cursor, etc.
Procedure:

(a) Document the capabilities and accuracy of each tool;

(b) Use a phantom with known dimensions and/or internal structures;
(c) Perform measurements of distance for known points;
(d) Verify that the results are correct, as well as how the co-ordinate systems are changed, if at all;
(e) Perform measurements in different directions, on different slices, with the display zoomed, etc.

9.3.3.19. Anatomy test 19: Basic co-ordinate system

Purpose: To verify the use (or capabilities) of the TPS co-ordinate systems compared with the co-ordinate systems used by the therapy machines and imaging systems in the department.

Procedure:

(a) Confirm the relationship to the standard co-ordinate system used by the radiation therapy machines for each co-ordinate system used in the anatomical model of the TPS. Typically there is an inherent co-ordinate system used for data acquisition, and a distinct (and potentially different) co-ordinate system used by the TPS.
(b) Confirm that identification of co-ordinates is correctly defined for the two different systems. In many TPSs, one can define one's own co-ordinate system origin, so this functionality must be confirmed. If the origin can be shifted, all anatomy and beam co-ordinates may need to change or be automatically recalculated: this should be checked. The dose calculation validity after such a change should also be checked.
(c) Recognize possible confusion in the longitudinal (along the table) direction: the longitudinal direction is traditionally called z in some systems, but it is now known as Y_I in the IEC [75] system. Depending on the CT scanner software and patient scan orientation, the CT slice numbering and Y_{CT} values may be different from those used in the TPS.

Note:

(1) If the TPS origin is different from the CT origin, the Y_{CT} values of the slices will be offset between the CT images and the TPS images.
(2) The orientation of the patient (prone versus supine) can also have an effect on the co-ordinate systems and/or the labelling of these co-ordinates.

9.3.3.20. Anatomy test 20: Three dimensional co-ordinate readout

Purpose: To demonstrate the read out of 3-D co-ordinates for known points in co-ordinate systems.

Procedure:

(a) Use a phantom CT image with known dimensions and/or internal structures for each tool;
(b) Align the co-ordinate system (or scan) so that individual points in the data set are known inside the co-ordinate system;
(c) Use the co-ordinate readout to give the TPS version of the co-ordinates and compare with the expected values;
(d) Analyse differences to identify any errors in the understanding of the co-ordinate systems.

9.3.3.21. Anatomy issue 1: Use of multiple image data sets and image registration

The use and testing of multiple data set capabilities, as used in image registration or other multiple imaging modality work, is beyond the scope of this report. A significant series of additional tests and procedures are required to commission this functionality, as illustrated by the following:

(a) Documentation of co-ordinate transforms between different data sets.
(b) Verification that individual parts of a data set (e.g. the sagittal images in a CT data set) are transformed correctly when image registration is performed. This implies that all the objects or entities that are part of each data set must be tested to confirm that they move, in all three dimensions, with the origin of the data set.
(c) The documentation and functionality by which each data set is transformed to the reference or base data set must be tested. Document the co-ordinate transforms between data sets.
(d) Point based, surface based, volume based and mutual information based registration methods may be used. Each method depends on algorithms and tools, and has important parameters controlling its behaviour. Each of these methods must be tested in detail.
(e) What are the limitations? Does the registration and/or fusion process handle image distortion? Are corrections to compensate for distortions available?

9.4. EXTERNAL BEAM COMMISSIONING

The discussion on the commissioning of external beam planning capabilities is separated into several sections:

(a) General issues for external beam commissioning are discussed in Section 9.4.1.
(b) Machine capabilities and the definition of the external beam plan technique are described in Section 9.4.2. These checks confirm the definition of the machine and beams, devices, and plan creation capabilities; dose calculations may be performed, but checks against measured dose calculations are not required.
(c) Commissioning tests for external beam dose calculations are described separately for photon beams (Section 9.4.3) and electron beams (Section 9.4.4). These sections summarize all the relative dose calculation checks that should be performed.
(d) General dose calculation algorithm operational issues are described in Section 9.4.5.
(e) Absolute dose, plan normalization and MU calculations are discussed in Section 9.4.6. These checks separate the crucial step of calculating the absolute dose or MUs that are used to define the way in which the plan will be delivered to the patient from the above steps.

9.4.1. General schema for external beam commissioning

9.4.1.1. Basic philosophy

The general aims of the dose calculation commissioning tests described in this report are:

(a) To identify or minimize the effects of errors or limitations in the dose calculation algorithm or its parameterization;
(b) To minimize uncertainties in routine use of the dose calculations, and to help keep them within the desired clinical tolerances;
(c) To characterize or demonstrate algorithm or implementation limitations, to prevent the inappropriate clinical use of the calculation results.

Complete characterization, algorithm validation and software testing of a dose calculation algorithm are typically beyond the capabilities of most institutions. This report therefore proposes a limited (though still extensive) set of tests that will help an individual institution make reasonable algorithm checks,

perform clinical commissioning and prepare a dose calculation algorithm for release for routine clinical use. The user must define the capabilities that will be used, provide appropriate data and analysis, and take responsibility for the verification of the features of the TPS and the dose calculation algorithms that will be tested and then used.

9.4.1.2. Methodology for dose calculation commissioning

For each dose calculation algorithm, and often for each separate beam (where 'beam' is a distinct energy and mode for a particular machine), a series of distinct steps are necessary to complete the commissioning process (Table 36).

9.4.1.3. Algorithm commissioning plan

To create a commissioning plan for each calculation algorithm, the user must:

(a) Consider any vendor recommendations;
(b) Identify commissioning issues for the calculation algorithm and the planned clinical use of the TPS;
(c) Define the required experiments (tests), evaluate all the required data and calculation comparisons, and combine tasks, if possible, to decrease the amount of work involved;
(d) Define the necessary measurement techniques to be used for the required data.

9.4.1.4. Measured data

The following general steps are involved in acquiring and using measured data:

(a) Evaluate the data required by the various tests included in the commissioning plan and organize the data for the most efficient collection.
(b) Determine which detectors and measurement techniques will be used for each data set and plan consistency checks between data obtained with different detectors to confirm the accuracy of the measured data [70].
(c) Check the accuracy of the measurement devices. The use of computer controlled water phantoms must include checks of the linearity and accuracy of the various motion controls, as well as an understanding of the different scanning modes. Each detector's operation should also be

TABLE 36. STEPS IN DOSE CALCULATION COMMISSIONING

Step	Goal	Description
1	Create a commissioning plan (Section 9.4.1.3)	Identify the algorithm type Identify specific issues for special attention Define an efficient plan for data collection, dose distribution comparisons and analysis of results
2	Obtain measured data (Section 9.4.1.4)	Plan, measure, transfer, analyse and prepare data for use
3	Check input data (Section 9.4.1.5)	Verify the correctness of input data
	(a) Configuration parameters	Confirm machine–beam configuration parameters
	(b) Algorithm input data	Verify that input data have been entered correctly
	(c) Model parameters	Determine beam model fitting parameters
4	Perform calculation checks (Section 9.4.1.6)	Compare beam specific calculations with measured data The design of the specific tests and analysis of the comparisons is a combination of the three types of check listed below
	(a) Beam specific calculation checks	Compare beam specific calculations with measured data to confirm that beam specific parameters are correctly set and that calculations give good results
	(b) Algorithm specific investigations	Test algorithms to confirm the proper behaviour of the algorithm Document algorithm accuracy on a test or benchmark data set Investigate specific algorithm issues
	(c) Clinical calculation verification	Verify that the calculations perform as expected in the user's hands Verify behaviour over the range of expected clinical usage and at the limits set for clinical use
5	Calculation comparison and analysis (Section 9.4.1.7)	Verify calculation techniques and plan comparison tools

verified. Film measurements require concurrent optical density to dose calibration curves, as well as confirmation that the film processor is maintained and working correctly [70].

(d) Make the measurements, including both basic data for model parameter determination and verification data, which are used for algorithm verification and calculation verification checks. Ensure proper documentation of each test situation (experiment).
(e) Ensure that the various measured data sets are self-consistent.
(f) Transfer the data from the measurement system to the TPS.
(g) Apply appropriate corrections, smoothing, renormalization and resampling to the measured data, if appropriate. These modifications of the raw data must be carefully quality controlled.

9.4.1.5. Algorithm input data

Input data for the algorithm include configuration parameters, algorithm parameters and fitting parameters. Implement a check procedure for all algorithm parameters as follows:

(a) Enter the correct value for each parameter input into the system;
(b) Document the parameters set in the system with a printout or written summary;
(c) Develop an independent check of these parameters, preferably by a second person.

(a) Configuration parameters

All calculation model implementations include various non-dose related parameters that describe the machine configuration and various algorithm specific parameters. The user should use a check procedure for this information, as described in Table 44.

These input parameters should describe the complete configuration of the system for the user. Examples include:

(1) Field size limitations;
(2) Machine list;
(3) Names of beams;
(4) External devices;
(5) The decay of the cobalt source;
(6) Default options;
(7) Brachytherapy sources.

Ideally, the TPS will provide a summary printout listing of all these parameters. If this is not available, then all parameters should be clearly documented in the TPS logbook (as in the above list).

(b) Algorithm input data

The verification of correct input parameters for the calculation algorithm works essentially as described for the non-dose related configuration parameters listed above. This check only confirms the parameters input, and does not involve any dose calculation checks.

Various techniques may be used to document the parameters, since there may be a large number of parameters in a data based model. The tolerance for agreement in reproducing the input data should be extremely tight (essentially identical). Basically, the user is looking for any differences between the expected and actual parameters.

Examples of ways to perform this check include:

(1) Printing out the model parameters, with a second person confirming the correct values.
(2) Plotting input data (if appropriate) with a program independent of the TPS calculation algorithm.
(3) Extracting data if appropriate tools are available. For algorithms based directly on measured input data, use the TPS to print or plot the basic input data used by the calculations. Note that in many algorithms, each additional machine capability (e.g. a wedge) or different planning technique may require additional data. All the data that are entered must be checked.

(c) Model parameters (fitting parameters)

Many models involve the use of some parameters that are fitted, meaning that the parameters are determined by choosing the value that gives the best dosimetric results. This fitting procedure usually involves iterative dose calculations (under either manual or automated control) using different values of the parameter. The process should obtain the best fit value of the parameter. How this fitting process works is dependent on the particular TPS. A typical semi-empirical calculation algorithm may use several measured depth dose curves for different field sizes, plus cross-beam profiles or isodose charts measured for the same field sizes, as the input data for the fitting procedure. The input data checks then will involve:

(1) Calculation of the depth dose curves for the field sizes used and comparison with the input data.

(2) For each of the field sizes used for profile or isodose chart input, calculation of (at least) the profiles or isodose charts used, and comparison with the input data.

Analysis of these results is different from simply checking that the data are being reproduced, because it is not expected that the calculations will exactly reproduce the input data. One must confirm here that the agreement between calculations and input data is acceptable, and that the data are representative of the agreement expected throughout the data set. Larger errors are often accepted in one area of the comparison (e.g. in the buildup region), in order to achieve better agreement in another area (e.g. the region near d_{max}).

For parameter dependent models, the results of the input data check typically will not exactly reproduce the original data. The accuracy with which the model can reproduce the data is quite variable, and depends both on the model and on the user's use of the model parameters. The accuracy achievable with each model should be provided by the vendor of the TPS or obtained from publications describing the use of the model. Typical tolerance limits on depth dose are 1–2%, while the tolerance for profiles can be 2–3% (or more) within the central part of the beam [18, 67]. Details are given in Section 5.3.3.

9.4.1.6. Calculation checks

(a) Beam specific calculation checks

After the basic input data are confirmed, the next step in commissioning is to compare beam specific dose calculations with measured data. Examples of these comparisons include a comparison of measured and calculated depth dose curves and comparisons between measured and calculated beam profiles at various depths for a number of different field sizes. The purpose of these checks is to confirm that the beam specific parameters in the calculation algorithm are correctly set, and that the doses calculated with the model agree well enough with the data for the calculations to be used clinically.

(b) Algorithm specific checks

It is also important to confirm that the algorithm is working correctly: this leads to a set of algorithm verification checks. The complete validation of the algorithm's correct behaviour is typically beyond the scope of the individual user, and should be performed by the vendor. However, it is the responsibility of the user to confirm that this has been done and to perform checks of the algorithm.

The user can perform algorithm verification checks using a test or benchmark data set, rather than necessarily having to use his or her own

measured data. This is particularly helpful for certain complex aspects of the algorithm verification tests, for example for complex inhomogeneities, for which the measurements themselves can be quite difficult.

The goal of algorithm tests is to confirm that the algorithm works correctly. This does not mean that the calculation results will always agree with the data, since many algorithms are approximate and will not agree exactly with measurements. Analysis of algorithm testing therefore requires that the user understand how the algorithm works and what kind of results should be expected. Vendors should provide enough information to users about their algorithms that these types of analysis can be performed.

(c) Clinical calculation verification

Dose calculation verification is often the main task involved in calculation algorithm commissioning. The verification process involves the design, performance and analysis of a number of calculation versus measurement (or reference data) checks. The tests to be used and the analysis of the test results depend on the following:

(1) Verification of correct behaviour of the calculations; for example, checking the isodose lines calculated for the same field size at several different SSDs may infer that the algorithm is performing the inverse square and divergent field projection calculations correctly.
(2) Assessment of accuracy: checks of the dose distribution obtained for several standard clinically used treatment plans may be performed to document for the physicians and other staff how accurate the dose calculation algorithm (as implemented by the TPS) is in those particular situations.
(3) Determination of the allowable limits for the clinical use of the dose calculations. It is often hard to conclude how robust a particular algorithm is and to test the accuracy of the calculations against data measured for extreme cases (cases designed to represent plans that are more complex or problematic than those that are going to be allowed to be used clinically). Note that this limit may expand over time as experience is gained.

There are two different types of calculation check, as listed in Table 37.

TABLE 37. CALCULATION VERIFICATION CHECKS

	Explanation
Beam dependent checks	Beam dependent checks must be performed for each photon and electron beam that will be used for clinical planning; these experimental situations are most directly affected by calculation model parameters and other user dependent input
Algorithm and clinical feature tests	These checks are more general than the beam parameter specific tests described above and need not (necessarily) be performed for each different beam, since basic algorithm issues will most likely be common to all beams that use that algorithm; these checks confirm the accuracy of important treatment planning functions and should be documented and understood by the physicists, physicians and treatment planners involved in clinical treatment planning

TABLE 38. CALCULATION AND COMPARISON TECHNIQUES

	Comparison techniques[a] [15, 80, 81]
1-D	Comparison of one or more depth dose and profile curves Table of differences of depth dose curves for several field sizes
2-D	Isodose line (IDL) comparison: plotted IDLs for calculated and measured data Dose difference display: subtract the calculated dose distribution from the measured distribution; highlight regions of under- and overexposure, if available Distance to agreement: plot the distance required for measured and calculated isodose lines to be in agreement, if available
3-D	Generate a 3-D measured dose distribution by interpolation of 2-D coronal dose distributions and a depth dose curve, if available DVH comparison of 3-D calculated and measured distributions, if available DVH of 3-D dose difference distribution, if available

[a] Different resolution calculations may be necessary to take into account the limits of the TPS.

9.4.1.7. Calculation and comparison techniques

Methods for dose calculation and comparison of calculations with measured data are listed in Table 38.

9.4.2. External beam plans: Machine capabilities and beams

Testing of the machine and of the external beam technique parts of the planning process is organized using Table 39, which lists the various issues involved in machine or beam definition and use. Tests that will confirm the basic behaviour of the beam related functionality of the TPS are listed in the table, and the tests are then described in more detail in the following sections.

Note that many of these beam tests are much easier to perform with the aid of a beam geometry phantom with adjustable orientations. However, although such phantoms are commercially available (e.g. see Ref. [15]), they are not considered standard QA items and are not essential for the tests described in this section.

Table 40 shows the tests to be performed if only basic capabilities (Table 25) are being used.

9.4.2.1. Beam test 1: Machine description and capabilities

Purpose: To check and document that the description of the machine, the beams and all related parameters have been entered into the TPS machine database correctly.

Procedure: Obtain (or create) a list of all components of the machine and beams, and then expand the list to contain each of the database parameters used to configure these components. Use the TPS utility, screen capture or other means to obtain a hard copy of the list and check that the list matches the details of the actual machines. An example list of beam defining parameters is shown below (from table 3-9 in Ref. [18]).

Example of beam parameters required to configure a beam:

(a) Beam parameters:
  (i) Machine;
  (ii) Modality;
  (iii) Energy.
(b) Beam geometry:
  (i) Isocentre location and table position;
  (ii) Gantry angle;
  (iii) Table angle;
  (iv) Collimator angle.
(c) Field definition:
  (i) Source to collimator distance;
  (ii) Source to tray distance;
  (iii) Source to MLC distance;

TABLE 39. MACHINE ISSUES REQUIRING VERIFICATION CHECKS

	Level of complexity	Test	Required	Test for each machine and beam?
Machine capabilities	Machine description and capabilities	Beam test 1	Yes	Yes
Machine parameters	Machine readout conventions and scales	Beam test 2	Yes	Yes
	Limitations	Beam test 3	Yes	Yes
Field size and shaping	Collimator jaw setting	Beam test 4	Yes	Yes
	Asymmetric jaws	Beam test 5	If used	Yes
	Blocks (and trays)	Beam test 6	If used	No
	MLC shape	Beam test 7	If used	Yes
	Automated field shaping	Beam test 8	If used	MLC: yes, blocks: no
Beam set-up	Set-up (SSD–SAD)	Beam test 9	Yes	Yes
	Beam location (x, y, z)	Beam test 10	Yes	No
	Gantry, collimator and table angle	Beam test 11	Yes	Yes
	Arcs	Beam test 12	If used	Yes
Accessories	Wedges	Beam test 13	If used	Yes
	Compensators	Beam test 14	If used	Yes
	Electron applicators	Beam test 15	If used	Yes
	Bolus	Beam test 16	If used	No
Beam display	Axial planes	Beam test 17	Yes	Yes
	Non-axial planes	Beam test 18	If used	Yes
	3-D displays	Beam test 19	If used	Yes
BEV	BEV display of beam and anatomy	Beam test 20	If used	Yes
	DRR calculation and display	Beam test 21	If used	Yes
	Display of portal images	Beam test 22	If used	Yes
Beam normalization	See Section 9.4.6			

TABLE 39. MACHINE ISSUES REQUIRING VERIFICATION CHECKS (cont.)

	Level of complexity	Test	Required	Test for each machine and beam?
Multiple beam tools	Multiple beam isocentre functions	Beam test 23	If used	No
	Field matching	Beam test 24	Yes	Yes
			If used	No
Special techniques	Missing tissue and dose compensation	Beam test 25	If used	Yes
	Inverse planned IMRT	Beam issue 1	If used	Yes
	Radiosurgery	Beam issue 2	If used	Yes
	Large field techniques (TBI, HBI, etc.)	Beam issue 3	If used	Yes
	Complex table motions (pseudo-isocentric and extended SSD planning)	Beam issue 4	If used	Yes
			If used	No

Note: Users should perform all the tests that describe situations that will be released for clinical use. Many of these issues are dependent on the machine or beam specific definitions contained in the TPS machine database, and so must be repeated for each beam and/or machine.

(iv) Collimator settings (symmetric or asymmetric);
(v) Aperture definition, block shape, MLC settings;
(vi) Electron applicators;
(vii) Skin collimation.

(d) Wedges:
(i) Name;
(ii) Type (physical, dynamic, automatic);
(iii) Angle;
(iv) Field size limitations;
(v) Orientations;
(vi) Accessory limitations (blocks, MLC, etc.).

(e) Beam modifiers:
(i) Photon compensators;
(ii) Photon and/or electron bolus;
(iii) Various types of intensity modulation.

TABLE 40. BASIC CAPABILITIES EXAMPLE

	Level of complexity	Test	Test for each machine and beam
Machine capabilities	Machine description and capabilities	Beam test 1	Yes
Machine parameters	Machine readout conventions and scales	Beam test 2	Yes
	Limitations	Beam test 3	Yes
Field size and shaping	Collimator jaw setting	Beam test 4	Yes
	Blocks (and trays)	Beam test 6	No
Beam set-up	Set-up (SSD–SAD)	Beam test 9	Yes
	Beam location (x, y, z)	Beam test 10	No
	Gantry and collimator	Beam test 11	Yes
Accessories	Wedges	Beam test 13	Yes
Beam display	Axial planes	Beam test 17	Yes
Beam normalization and weight	Definition of beam normalization and relative weights (see Section 9.4.6)		
Multiple beam tools	Multiple beam isocentre functions	Beam test 23	No

(f) Normalizations:
  (i) Beam weight or dose at beam normalization point;
  (ii) Plan normalization.

9.4.2.2. Beam test 2: Machine readout conventions and scales

Purpose: To check that all display co-ordinate systems, labels and names of parameters used by the TPS agree with those used on the modelled treatment machines, to avoid any mistreatments due to incorrect conversion of information between the TPS and the treatment machine.

Procedure:

(a) For each separate treatment machine that will be implemented within the TPS, use the list from beam test 1.
(b) Create treatment plans that illustrate the use of all such parameters, including multiple positions of each motion axis (angles such as gantry, collimator and table, linear motions such as table x, y, z, collimation motions such as jaws, etc.), so that the direction and magnitude of the co-ordinates are checked.
(c) Transfer the output of the TPS to the treatment machine in the clinically desired way and confirm that the setting of the machine for each field agrees exactly with the created plan.
(d) Confirm and document each parameter for each field and plan. Labels and names must also be confirmed in a similar fashion. Particular attention should be paid to jaw labels ($x1$, $x2$, $y1$ and $y2$), wedge names and direction codes, MLC leaf names, etc.

Note that angles are typically defined in degrees, but that the default position and direction of increasing angle is different for different machines. Linear scales are also different, and may be noted in cm or in mm. Although Refs [37, 75] are recommended for use by all vendors of accelerators and TPSs, multiple co-ordinate systems are still in use and it is important to confirm that the chosen co-ordinate system is implemented correctly.

9.4.2.3. Beam test 3: Machine parameter limitations

Purpose: To check that the TPS prevents the entry of machine parameters that are outside the limits set during configuration.

Procedure:

(a) Use the list from beam test 1 for each separate machine.
(b) Attempt to enter values greater than the upper limit and less than the lower limit for SSD, collimators (unwedged and wedged), MLC opening, etc. Note any limits that are not observed by the TPS.

9.4.2.4. Beam test 4: Collimator jaw setting

Purpose: To check that all possible symmetric collimator settings are accepted and interpreted correctly by the TPS.

Procedure:

(a) Set fields for each separate machine corresponding to the minimum and maximum squares and for some intermediate rectangles (e.g. 10 cm × 20 cm).
(b) Check that the field sizes and shapes are correct as represented on a transverse contour and BEVs. For the rectangles, rotate the collimator through 90° and check that the fields are still correct.

9.4.2.5. Beam test 5: Asymmetric jaws

Purpose: To check that all possible asymmetric collimator settings are accepted and interpreted correctly by the TPS.
Procedure:

(a) Set fields for each separate machine corresponding to the asymmetric extremes (e.g. $x1 = 20$ cm, $x2 = -15$ cm) and for some intermediate asymmetric rectangles (e.g. 10 cm × 20 cm).
(b) Check that the field sizes and shapes are correct as represented on a transverse contour and in the BEVs. For each field, rotate the collimator through 90° and check that the fields are still correct.

9.4.2.6. Beam test 6: Block definitions and shapes

Purpose: To check that blocks are correctly stored and displayed.
Procedure:

(a) Enter blocks of regular shapes and known geometry (corner blocks, central blocks and half-beam blocks) and check that the blocks are correctly represented on transverse contours and in the BEVs.
(b) If blocks can be saved to a library, check that they can be identified and recalled. The plan should be saved, then recalled and checked that the blocks are still correct.

9.4.2.7. Beam test 7: Multileaf collimator shaping

Purpose: To check that MLC shapes are correctly stored and displayed.
Procedure:

(a) Enter MLC shapes of regular and known geometry (e.g. rectangle, T shape, diamond shape, staircase) and check that the shapes are correctly represented on transverse contours and in the BEVs;
(b) The plan should be saved, then recalled and checked that the MLC shapes are still correct.

9.4.2.8. Beam test 8: Automated field shaping

Purpose: To check that field shapes defined by conforming to the shape of a target volume are the correct size and shape.

Procedure:

(a) Draw a box shaped target volume of known dimensions by drawing a square on one slice and copying it to the others.
(b) Use the automargin function for an anterior beam to create a beam shape with a 1 cm margin around the target.
(c) Check by examination of transverse slices and BEV that the margin has been correctly applied; repeat for blocks and the MLC if appropriate and repeat using different margins in orthogonal directions if that function is available.
(d) Create an ovoid shaped target and repeat the above, then create an irregular target, including a region of concavity, and repeat.

9.4.2.9. Beam test 9: Beam set-up

Purpose: To check that the TPS correctly sets the beam geometry for both SAD and SSD type set-ups.

Procedure:

(a) Enter an isocentric (SAD) 10 cm × 10 cm beam at a depth of 10 cm using images of a test phantom;
(b) Check that the SSD is reported as SAD minus 10 cm, and that the field size at the surface is correctly reduced;
(c) Add a second beam from the same direction but defined as SSD and positioned on the surface and check that it is correctly sized;
(d) Move the beam isocentre and entry points and, if the TPS allows, toggle each beam between SAD and SSD set-ups and check for correct behaviour.

9.4.2.10. Beam test 10: Beam location

Purpose: To check that beams are correctly positioned with respect to the patient co-ordinate system.

Procedure:

(a) Establish the patient co-ordinate system used by the TPS and establish the origin of this system for images of a test phantom;
(b) Enter a beam with isocentre or entry co-ordinates x, y, z and check that it is correctly positioned (i.e. correctly displayed on the screen and with correct distances and directions from the patient origin in all three axes);
(c) Move the beam by varying each co-ordinate in turn and check for correct behaviour;
(d) Check how the TPS handles such issues as an isocentre outside the patient and an SSD beam that is not positioned on the surface: is it moved to the surface or is a different SSD determined?

9.4.2.11. Beam test 11: Gantry, collimator and table angles

Purpose: To check that beam outlines are correctly positioned and correctly projected onto image planes, for the range of possible machine angles.

Procedure:

(a) Gantry angles: Confirm the correct beam direction (with both display graphics and dose distribution) for gantry angles (at least every 90º) from one gantry motion limit to the other. Use examples from appendix 3 of Ref. [18] plus additional shapes. Look at the dose distribution versus beam graphics and check the gantry angles. Using a square phantom, calculate the dose from beams from various directions, and confirm that the dose distribution from each direction is the same.
(b) All angles: Use plans that change only one parameter to confirm the angle display, geometric correctness and dose distribution calculated over the entire range of motion for the gantry angle, collimator angle and table angle. Confirm the correct beam direction (with both display graphics and dose distribution) for plans that combine non-standard gantry, collimator and table angles.

9.4.2.12. Beam test 12: Arcs

Purpose: To check that arc parameters are handled correctly.

Procedure:

(a) Angle readout: Confirm the correct arc angle start and stop for relevant arc beams with the beam moving in both clockwise and counterclockwise directions for a 90º arc and a 150º arc.
(b) MUs/degree: Confirm the correct values of MUs/degree for 90º and 150º arcs, using, for example, 100 and 300 MU per field.

9.4.2.13. Beam test 13: Wedges (hard, motorized and dynamic)

Purpose: To check that wedges are applied and displayed correctly.
Procedure:

(a) Select each wedge, and each wedge direction, and perform a simple dose calculation to confirm that the wedge has been selected and that both the graphics describing the wedge and the wedge shaped dose distribution are correctly orientated.
(b) Check that the wedge rotates correctly when the collimator is rotated. These are not calculation checks, just functional checks to demonstrate that the wedge dose distribution appears to be correct.
(c) For each wedge, enter field sizes that are too large for that wedge and check that the wedge cannot be selected. Similarly, change the field size to too large after selecting the wedge.
(d) Repeat for small fields if a lower field size limit can be set.
(e) Repeat for asymmetric jaws, to ensure that invalid jaw–wedge combinations are disallowed.

9.4.2.14. Beam test 14: Compensators

Purpose: To check that compensators are correctly applied and displayed.
Procedure: This will depend on the particular TPS. For those that calculate a missing tissue compensator, create a compensator for a beam incident on a phantom at an angle of 30° and check that the compensator is correctly orientated and looks reasonable. Check whether the compensator is removed if the gantry or collimator angles are changed or if the field size is altered.

9.4.2.15. Beam test 15: Electron applicators

Purpose: To check that electron applicators can be selected and are handled correctly.

Procedure:

(a) Depending on the TPS (some do not specifically consider the electron applicator when defining beams), select each applicator and check that it is displayed correctly.
(b) See if the TPS prohibits cases in which the field aperture is larger than the applicator dimensions and where the SSD is set such that in reality the applicator would collide with the patient.

9.4.2.16. Beam test 16: Bolus

Purpose: To check how the TPS handles the addition and display of bolus.
Procedure: Bolus may be entered in various ways, depending on the TPS. It may be added to contiguous transverse slices, as a constant thickness or manually drawn with variable thickness. It may also be entered as layers of different thicknesses by drawing a region on a BEV. It may be treated as if it is part of the patient's anatomy or it may be linked to a beam. It may or may not be possible to assign it a specific density. Test that the bolus function works as expected, that it can be created, displayed, edited, assigned and removed.

9.4.2.17. Beam test 17: Beam display on axial planes

Purpose: To check that beams are correctly displayed on axial slices.
Procedure:

(a) If a suitable test phantom including geometrical shapes is available (e.g. see Ref. [15]), obtain a CT image set, otherwise an anthropomorphic phantom or patient CT will suffice;
(b) Position the isocentre of a 10 cm × 10 cm beam on a particular slice, gantry 0°, collimator 0°;
(c) Check the display, noting the indication of the central ray and field size (diverging beam edges);
(d) Move to a slice 5 cm away and check whether there is an indication that the projection of the collimator position cuts that slice at the level of the isocentre.

9.4.2.18. Beam test 18: Beam display on non-axial planes

Purpose: To check that beams are correctly displayed on non-axial slices.
Procedure:

(a) Using the same CT data set and beam as in beam test 17, check the beam outline on a sagittal slice through the beam centre, a sagittal slice 5 cm away, a coronal slice through the isocentre and a coronal slice 5 cm anterior to the isocentre;
(b) Rotate the gantry through 90° and check again.

9.4.2.19. Beam test 19: Three dimensional beam displays

Purpose: To check that beams are correctly displayed in 3-D views.
Procedure:

(a) Using the same CT data set and beam as in beam test 17, check the representation of the beam in a 3-D view;
(b) Rotate the view in a variety of directions, zoom the view in and out and check that the relationship between the beam and the patient's anatomy does not vary;
(c) Rotate the beam collimator, gantry and treatment couch through a variety of angles and see that the beam outline moves as expected relative to the anatomy.

9.4.2.20. Beam test 20: Beam's eye view display of beam and anatomy

Purpose: To check that the BEV shows the correct relationship between the beam and the anatomy.
Procedure:

(a) Using the same CT data set and beam as in beam test 17, study the BEV, noting the relationship between the beam edges and structures within the phantom that have been contoured.
(b) Move the beam's position and check that the display updates appropriately. Make use of known structure sizes or anatomical distances.
(c) Move the beam's isocentre deeper and shallower and check for correct behaviour.

9.4.2.21. Beam test 21: Digitally reconstructed radiograph calculation and display

Purpose: To check that DRRs are calculated and displayed correctly.
Procedure: A detailed check of a DRR algorithm is complex and beyond the scope of this report. However, some basic checks similar to beam test 20

can be performed, the difference being that in this test the position of the beam outline is compared with features on the DRR, not outlined objects.

9.4.2.22. Beam test 22: Display of portal images

Purpose: To check that portal images match and can be correlated or registered correctly with the corresponding DRR image.

Procedure: If the TPS allows import of either electronic portal images or scanned films, use the phantom from beam test 17 to generate portal images. Check that they match the corresponding DRR and check the functionality of image scaling and registration tools, if any.

9.4.2.23. Beam test 23: Multiple beam isocentre functions

Purpose: To check that beams that are marked as having a common isocentre behave accordingly.

Procedure:

(a) Set up a multibeam plan and mark some beams as having a common (linked) isocentre and some as not;
(b) Move the isocentre of one of the linked beams and check that all linked beams move and that all unlinked beams do not;
(c) Move the isocentre of one of the unlinked beams and check that only it moves.

9.4.2.24. Beam test 24: Field matching

Purpose: To check that the edges of adjacent fields align correctly.

Procedure:

(a) Position the centres of two symmetric 10 cm × 10 cm fields so that their diverging edges are adjacent and check that the displayed beam edges intersect at the correct depth (e.g. the depth of the isocentre);
(b) Adjust the field size of the beams and check that the intersection point moves as expected;
(c) Position two beams with a common isocentre, creating a complementary pair of adjacent beams (e.g. jaws at 5 cm and 2 cm for one beam and –2 cm and 5 cm for the other), and check that the adjacent beam edges are coincident.

9.4.2.25. Beam test 25: Missing tissue and dose compensation

Detailed tests to see if the TPS calculates a compensator correctly are beyond the scope of this report. See photon test 14.

9.4.2.26. Beam issue 1: Inverse planned intensity modulated radiation therapy

Comprehensive additional commissioning and QA procedures are required to validate inverse planned IMRT and leaf sequencing algorithms. TPS predicted doses cannot be checked by measurements or manual calculations using the same methodology as for forward planning. Detailed checks of the dynamic MLC or other delivery device must be conducted, for example for leaf position calibration, interleaf effects, small field output factors, linearity of dose per MU and the relationship of jaws to MLC leaves. Leaf sequences must be exported to the linear accelerator and delivered to appropriate phantoms. The absolute dose and spatial distribution of the dose are then measured using ionization chambers, film, thermoluminescent dosimeters or gel dosimeter, and are compared with the predicted dose.

The details of these procedures depend strongly on the particular inverse planning software of the TPS and on the linear accelerator and delivery device. This report does not discuss inverse planned IMRT any further.

9.4.2.27. Beam issue 2: Radiosurgery

Although specific photon beam tests are required for radiosurgery, it is inappropriate to detail these special requirements without discussing them in the context of the entire radiosurgery process. A detailed discussion of this process is beyond the scope of this report; some of the important issues for further consideration [82] are, however:

(a) Frame co-ordinates;
(b) Better positional accuracy required (sub-millimetre);
(c) Registration of frame and CT co-ordinates;
(d) Image registration;
(e) Circular applicators versus mini-MLCs versus MLC versus Gamma Knife;
(f) Small field dosimetry (output factors, collimator scatter factors (S_c) and phantom scatter factors (S_p) are very sensitive to field size);
(g) Measurement difficulties (small fields need special detectors);
(h) Large doses per fraction (up to 20 Gy per fraction);
(i) Non-coplanar fields and arcs.

Many radiosurgery techniques involve the use of a specialized set of small circular (or another shape) applicators. Given that each applicator has a different dosimetric situation, it is essential to measure and verify the behaviour of the dose calculation algorithm for each applicator for each energy used.

Dose calculations for small fields require enhanced attention to precision, as 1 mm field size differences can cause significant changes in output and/or the overall dose distribution. Care must thus be taken in the choice of dosimetric measurement devices, calculation grid sizes and all size and resolution aspects of both measurements and calculations.

For each applicator the following priorities apply:

(a) Priority 1:
  (i) The central axis depth dose;
  (ii) The central axis normalization point output factor;
  (iii) Transverse dose profiles at $d = d_{max}$, $d = 10$ cm and $d = 20$ cm (three depths minimum).

(b) Priority 2:
  (i) Completion of a 2-D dose profile for a transverse slice.

9.4.2.28. Beam issue 3: Large field techniques

Large field irradiation at an extended SSD can be used for TBI with photons, prior to bone marrow transplantation, half-body irradiation (HBI) and total skin electron irradiation (TSEI). The procedures required to measure the relevant beam data differ from the usual beam data acquisition and are not covered in this report. Many TPSs do not support such large fields at all, because of limits in the maximum SSD or field size. TPSs that do not explicitly prevent the required geometry may nevertheless not handle it, either in beam display or with dose calculation, since algorithms may be extended well beyond their intended range of application. It may be possible to configure a treatment unit for a specific purpose such as TBI, but a discussion of the issues involved is not given in this report. See Ref. [83] for a more detailed discussion of TBI, HBI and TSEI.

9.4.2.29. Beam issue 4: Complex table motions

Some treatment techniques use table movements, either between beams (e.g. to produce a pseudo-isocentre at a greater treatment distance) or between partial beam segments (e.g. to blur the leaf width effect of an MLC). A recent advance is helical tomotherapy, in which the couch moves as the gantry rotates,

effectively giving a spiral beam [84]. Planning for such table movements is not dealt with in this report.

9.4.3. Photon beam commissioning

High energy photon beams created by linear accelerators (or other similar devices) are discussed in this section.

TABLE 41. PHOTON BEAM DOSE CALCULATION CAPABILITIES
(Note the techniques that are likely to be used and then perform tests for these issues. These issues need to be combined with the testing listed in Table 42.)

	Feature
Collimation	Jaws Asymmetric jaws Blocks and trays MLCs Small fields Radiosurgery applicators
Beam angles	Fixed 2-D Fixed 3-D 2-D dynamic (gantry arc) 3-D dynamic
Beam set-up	SSD set-up Isocentric set-up Complex table motions, pseudo-isocentre
Wedges	Physical wedges Motorized wedge Dynamic wedge
Compensators	Manually created compensators Computer fabricated compensators
Density correction algorithms	1-D (effective path length) 2-D (equivalent tissue air ratio, etc.) 3-D
Special techniques	Radiosurgery Large field techniques Multisegment IMRT Dynamic MLC IMRT

9.4.3.1. Photon dose calculation issues

The first step in planning the commissioning is to plan the issues that need to be tested. Note the relevant issues listed in Table 41 and combine them with the tests listed in Table 42.

Table 43 shows the reduced tests to be performed if only basic capabilities (Table 25) are being used.

9.4.3.2. Experimental methods for photons

Each institute should have a standard set of data and experimental methods for the acquisition of those data. These can vary between institutions, but should be consistently defined for each institution.

Although traditionally most basic data have been measured at a 100 cm SSD, this may no longer be optimal when isocentric treatments are normally used. Therefore, while it is preferred that the standard SSD for most types of photon treatment should be 90 cm, for some TPSs it is important to adhere to the vendor's recommendations, which may correspond to an SSD of 100 cm. Suggestions for standard photon data set procedures are listed in Table 44.

9.4.3.3. Tests for photons

The following test comparisons should be performed and documented in order to assess the accuracy of dose calculations and to document behaviour for clinical analysis of the results.

9.4.3.4. Photon test 1: Square and rectangular fields

Purpose: To verify agreement over the range of symmetric field sizes to be used clinically.

Procedure: The tests described below should be performed with MLCs and/or jaws, depending on which collimation is more commonly used in the clinic.

Compare measurements and calculations using 1-D (depth dose and cross-beam profiles) or 2-D dose distributions. Check:

(a) Square fields, for example 5 cm × 5 cm, 10 cm × 10 cm, 40 cm × 40 cm (or maximum). If fields are smaller than 5 cm × 5 cm, then the smallest field should also be measured.

TABLE 42. PHOTON BEAM PLANNING TECHNIQUES REQUIRING VERIFICATION CHECKS

(Users should check which levels of complexity will be used, and perform the tests listed.)

	Issue	Test
Field shaping	Square and rectangular fields	Photon test 1
	Asymmetric fields	Photon test 2
	Shaped fields	Photon test 3
Beam directions	Fixed fields	Photon test 4
	Arc rotations	Photon test 5
SSD	SSD dependence	Photon test 6
Wedges	Mechanical (hard) wedges	Photon test 7
	Automatic wedge	Photon test 8
	Dynamic wedge	Photon test 9
Patient shape	Oblique incidence	Photon test 10
	Missing scatter	Photon test 11
Buildup region	Buildup region behaviour	Photon test 12
Inhomogeneities	Density corrections	Photon test 13
Special techniques	Missing tissue and dose compensation	Photon test 14
	Forward planned IMRT	Photon test 15
	Inverse planned IMRT	Photon issue 1
	Radiosurgery	Photon issue 2
	Large field techniques (TBI, HBI, etc.)	Photon issue 3

TABLE 43. BASIC PLANNING TECHNIQUES FOR PHOTON BEAMS REQUIRING VERIFICATION CHECKS

	Issue	Test
Field shaping	Square and rectangular fields	Photon test 1
	Shaped fields	Photon test 3
Beam directions	Fixed fields	Photon test 4
	Arc rotations	Photon test 5
SSD	SSD dependence	Photon test 6
Wedges	Mechanical (hard) wedges	Photon test 7
Patient shape	Oblique incidence	Photon test 10
	Missing scatter	Photon test 11
Buildup region	Buildup region behaviour	Photon test 12
Inhomogeneities	Density corrections	Photon test 13

TABLE 44. PHOTON DATA SET PROCEDURES

	Desired	Details
SSD used for basic data	SSD = 90 cm or 100 cm	It is important to follow the recommendations of the TPS vendor
Phantom material	Water	The water phantom should contain full scatter (small water phantoms are suitable only for small field situations)
	Solid water	Solid water is suitable for certain situations if cross-checked with water measurements; confirm that there are no voids or low densities in the solid water, as these have been observed in some cases
Detectors	Ionization chamber	0.2 cm^3 ionization chamber or smaller for profiles A 0.6 cm^3 cylindrical ionization chamber is often used for point (integration) measurements (in low dose gradient regions only) Thin window parallel-plate chamber for buildup region measurements [70]
	Diodes	Small diodes are used for profiles when compared with ionization chambers
	Film	Radiographic film for 2-D (orthogonal to beam axis) dose distributions (Kodak XV, ECL or radiochromic film) [70]
	Arrays	An ionization chamber array can be used for dynamic delivery modes (dynamic wedge or DMLC) [70] Diode arrays can be used when compared with the ionization chamber standard [70]
Beam stability	Stable	Must confirm stability versus time for scanning, which requires long beam-on times

(b) Rectangular fields, for example 5 cm × 30 cm, 30 cm × 5 cm. If fields smaller than 5 cm wide are used, then the smallest field should also be measured.
(c) At several depths, for example at $d = d_{max}$, 10 cm and 20 cm.

Comparisons should be performed for diagonal and off-axis locations or in a 2-D plane orthogonal to the central axis. Tests should be performed using the standard set-up, either 90 cm SSD (for isocentric treatments on 100 cm machines) or the standard SSD.

Also check the depth dose and profiles at distances and depths outside the range of the measured data (i.e. where extrapolation is occurring).

9.4.3.5. Photon test 2: Asymmetric fields

Purpose: To verify agreement over the range of asymmetric field sizes to be used clinically.

Procedure: The tests described below should be performed with MLCs and/or jaws, depending on which collimation is more commonly used in the clinic. Compare measurements and calculations using 1-D (depth dose and cross-beam profiles) or 2-D dose distributions.

Check:

(a) The 10 cm × 10 cm field with x jaw or leaf edges set to zero (i.e. at the isocentre), then the y jaw or leaf edges, then both.
(b) Fields with the maximum allowed overtravel in the x and y axes.

Repeat the above with the maximum wedge angle for each type of wedge used (hard, motorized or dynamic).

Note that combinations of use of wedges with asymmetric jaws or shaped fields can be potentially quite complicated and must be confirmed. A set of tests that combine the following should be included in such cases:

(1) Wedged fields with asymmetric jaws: several different example cases.
(2) Shaped fields with asymmetric jaws and wedges.

9.4.3.6. Photon test 3: Shaped fields

Purpose: To verify agreement for a representative set of shaped fields.

Procedure: Tests should be performed for fields created with jaws and blocks or MLCs. Compare the central axis depth dose, output and profiles at $d = d_{max}$, 10 cm and 20 cm at two or three locations in the field. Work in absolute dose.

(a) Shape 1: 20 cm × 20 cm field with a cord block. At the central axis.
(b) Shape 2: 20 cm × 20 cm field with four corner blocks and added central block not extending through the central axis.
(c) Shape 3: Convex aperture. Generally oval shape, not symmetric.
(d) Shape 4: Concave aperture. C shape, central axis under block.

For routine use of more complex field shapes, example complex shapes should be added to this test.

9.4.3.7. Photon test 4: Fixed beams

Purpose: To check that fixed SSD beams are calculated correctly.

Procedure: Confirm the correct dose distribution for gantry angles (at least every 90º) from one gantry motion limit to the other. Use examples from appendix 3 of Ref. [18].

(a) Look at the dose distribution versus beam graphics and use knowledge of the gantry angles.
(b) Use a square phantom and calculate the dose from the beams from various directions. Confirm that the dose distribution is the same from each direction. (A cubic phantom allows non-axial fields.)

9.4.3.8. Photon test 5: Two dimensional arc rotations

Purpose: To check that 2-D arc rotations are calculated correctly.

Procedure: Verify the following:

(a) MU/time. Check MU/time calculations for a specified arc against a manual calculation or experimental measurement. Perform a manual calculation using the method given in Ref. [85], pp. 200–205.
(b) Dose distribution. Verify the correct dose distribution based on addition of an appropriate number of fixed fields, typically every 10° (since most arc rotation calculations are based on multiple fixed fields added together).

9.4.3.9. Photon test 6: Source to surface distance dependence

Purpose: To check the accuracy of the dose calculation for different SSDs.

Procedure: For the smallest and largest SSD likely to be used clinically, perform a self-consistency check of divergence, inverse square correction and profile shapes. Check for a single, standard field size (10 cm × 10 cm). If large irregularly shaped fields (e.g. mantle) are used at extended SSDs, make a measurement check at the standard extended SSD used for those treatments. Central axis, output and profile checks should be measured in a water phantom. A possible source of error is the actual field size (in the patient), which might be larger than the largest measured (parameterized) data in the TPS. This may cause extrapolation or truncation errors in the calculation.

9.4.3.10. Photon test 7: Hard wedges

Purpose: To check the accuracy of the relative dose calculation for hard wedges.

Procedure: For each hard wedge check:

(a) 5 cm × 5 cm, 10 cm × 10 cm and the maximum field size allowed with a wedge. Compare the measured and calculated depth dose (central axis) and profiles at $d = d_{max}$, 10 cm in the wedged direction and perpendicular to the wedged direction at the standard SSD (a 90 cm SSD is recommended).
(b) Compare profiles and the depth dose against measured data for 20 cm × 20 cm or the maximum field size field at an 80 cm SSD.

9.4.3.11. Photon test 8: Motorized wedge

Purpose: To check the accuracy of the relative dose calculation for a motorized wedge.

Procedure: For each motorized wedge (largest wedge angle available) check:

(a) 5 cm × 5 cm, 10 cm × 10 cm and the maximum field size allowed with the wedge. Compare the measured and calculated depth dose (central axis) and profiles at $d = d_{max}$, 10 cm in the wedged direction and perpendicular to the wedged direction at the standard SSD (an 90 cm SSD is recommended).
(b) Compare profiles and depth dose against measured data for 20 cm × 20 cm or the maximum field size field at an 80 cm SSD.

For a series of effective or nominal wedge angles (e.g. 15º, 30º and 45º for a typical maximum wedge angle of 60º):

(1) Check the dose distribution. Create the expected dose distribution for the effective wedge angle by adding an open field dose calculation and wedged field dose calculation with the correct fractional weights. Perform for the maximum field size allowed with the wedge. Compare the depth dose (central axis) and profiles at $d = d_{max}$, 10 cm, in the wedged direction and perpendicular to the wedged direction at the standard SSD (a 90 cm SSD is recommended).
(2) For the maximum field size, compare integrated ionization chamber measurements for the central axis point (d = 10 cm) and off-axis point

(d = 10 cm, 7 cm off-axis) using each effective wedge with those predicted by the TPS.

9.4.3.12. Photon test 9: Dynamic (virtual) wedge

Purpose: To check the accuracy of the relative dose calculation for dynamic (virtual) wedges (moving collimator).

Procedure: The dynamic wedge output varies dramatically with the orientation of the field size (a wedged field $A \times B$ may be quite different from $B \times A$) (see also asymmetric field tests, as asymmetric fields dramatically affect these results). The following tests are therefore required for each dynamic wedge angle:

(a) 5 cm × 5 cm, 10 cm × 10 cm, the maximum field size, 5 cm × 20 cm and 20 cm × 5 cm field sizes. Compare the measured and calculated depth dose (central axis) and profiles at $d = d_{max}$, 10 cm, in the wedged direction and perpendicular to the wedged direction at the standard SSD (a 90 cm SSD is recommended).
(b) Compare profiles and depth dose against measured data for 20 cm × 20 cm or the maximum field size field at an 80 cm SSD.

For a series of effective or nominal wedge angles (e.g. 15º, 30º and 45º for a typical wedge maximum of 60º):

(1) Check the dose distribution. Create an expected dose distribution for the effective wedge angle by adding an open field dose calculation and a wedged field dose calculation with the correct fractional weights. Compare the depth dose (central axis) and profiles at $d = d_{max}$, 10 cm, in the wedged direction and perpendicular to the wedged direction at the standard SSD (a 90 cm SSD is recommended). Check that the TPS doses look reasonable.
(2) For the maximum field size, compare the integrated ionization chamber measurements for the central axis point (d = 10 cm) and the off-axis point (d = 10 cm, 7 cm off-axis) using each effective wedge with those predicted by the TPS. An alternative to point dose measurements is a linear detector array or film measurements to give a more complete check.

For asymmetric fields (asymmetric in the wedged direction) used with a dynamic wedge, additional tests are required for the same series of effective or nominal wedge angles:

(i) For a 10 cm × 10 cm field size with maximum asymmetry (i.e. the maximum distance from the nominal central axis), make integrated ionization chamber measurements at d = 10 cm for a point at the centre of the asymmetric field and for a point 3 cm from a point at the centre along the wedged direction, compared with the central axis point for a symmetric 10 cm × 10 cm field size. Compare the measurements and TPS predictions.
(ii) For a field size of 10 cm × 10 cm with one edge at the central axis and moving the jaw away from the central axis, make integrated ionization chamber measurements at d = 10 cm for a point at the centre of an asymmetric field and for two points 3 cm from either side of a point at the centre along the wedged direction, compared with the central axis point for a symmetric 10 cm × 10 cm field size. Compare the measurements and TPS predictions.

9.4.3.13. Photon test 10: Oblique incidence

Purpose: To check how well the TPS predicts dose when the beam direction is oblique to the patient's incident surface.

Procedure:

(a) For a standard set-up (e.g. a 90 cm SSD, AP set-up, on a flat phantom) with a 10 cm × 10 cm field size, measure the 2-D transverse dose distribution for a 30º gantry angle;
(b) Obtain an isodose chart if possible, otherwise compare profiles or a selection of points with the corresponding TPS output.

9.4.3.14. Photon test 11: Missing scatter

Purpose: To check how well the TPS predicts dose changes when part of the beam misses the patient.

Procedure: Use a 20 cm × 20 cm field irradiating a square phantom with various amounts of missing scatter. Perform calculations for the AP set-up with several different field locations on the square phantom, including the case with the beam central axis placed off the edge of the phantom, d = 10 cm. Three possibilities exist for this test:

(a) Perform the calculation and determine if the algorithm takes the missing scatter into account qualitatively;
(b) Compare the results with measured data;

(c) Compare the results to benchmark data [86] (see the figures in the Annex).

9.4.3.15. Photon test 12: Buildup region behaviour

Purpose: To check how accurately the TPS calculates doses in the buildup region.

Procedure:

(a) Depending on the TPS, it may be possible to generate depth dose curves explicitly, or the data may be obtained by interpolation from a calculation grid dose matrix.
(b) Choose a method that maximizes resolution (e.g. small grid point spacing).
(c) Compare depth dose curves in the buildup region. If a parallel-plate or other appropriate chamber is available, accurate measurements can be made to shallow depths (0.2 cm). If only a cylindrical chamber is available, data may be accurate only at depths greater than 0.5 cm.

While these tests are not intended to test the behaviour in detail at the surface, since measurement of the dose at the surface requires careful dosimetric techniques using parallel-plate ionization chambers, extrapolation chambers or other suitable detectors, they are intended to give a general idea of what type of accuracy might be achievable.

Note also that TPSs generally do not calculate buildup region doses with high precision, because of limitations in the dose algorithm and the need to interpolate between calculation grid points. Accordingly, Section 5.3.3 gives larger tolerances for the buildup region.

Study the variation of the dose in the buildup region with field size and the addition of ancillary devices such as trays and wedges. (Note that the dose also varies with SSD and off-axis distance, obliquity, etc., but that these are not tested here.)

Compare calculations with central axis measurements:

(1) Field size: 5 cm × 5 cm, 10 cm × 10 cm, 30 cm × 30 cm.
(2) With and without a blocking tray.
(3) Unwedged and for the maximum hard wedge angle.

9.4.3.16. Photon test 13: Density correction

Purpose: To check the accuracy of the TPS's inhomogeneity correction algorithms.

Procedure: If users have a suitable slab phantom in which the dose distribution can be determined experimentally, then the phantom can be scanned, the CT images can be transferred to the TPS and the computed dose compared with the measurement. Otherwise, the benchmark data from Ref. [87] can be compared with output from the TPS for the same geometry. The data in Ref. [87] are for 4 MV and 15 MV. Although these energies may not match the user's beams, it should be possible to check for reasonable agreement.

Similarly, for profiles in the lungs, and the central axis dose at interfaces, experimental data could be obtained, but otherwise benchmark data from Ref. [88] for 6 MV and 18 MV may be used. Again, even if the user's beams are different, comparisons should show whether the TPS is able to predict the effects of electronic disequilibrium at field edges and interfaces. Use two test cases per energy. Use a slab lung geometry in a 20 cm × 20 cm field (large field) and in a 5 cm × 5 cm field (small field). Compare the central axis data.

Compare with benchmark data provided in fig. 2 of Ref. [87] (see the figures in the Annex).

The user should also perform profile calculations in the inhomogeneity or other phantom configuration, which will demonstrate loss of lateral scatter equilibrium. The benchmark data in Ref. [88] can be used for 6 MV and 18 MV X rays (see the figures in the Annex).

Very low densities inside or outside the patient (patients with emphysema, etc.) and high densities (bones, metal implants, teeth fillings and administered contrast) that produce CT artifacts can cause errors in dose calculation. These issues are discussed in Section 11.

9.4.3.17. Photon test 14: Compensation

Detailed tests to see if the TPS calculates a compensator correctly are beyond the scope of this report. However, some simple tests can show whether a homogeneous dose is predicted and achieved; for example, with a beam incident on a slab phantom at a 30° gantry angle, design a compensator to give a uniform dose in a horizontal plane. Export and manufacture the designed compensator and, using a water tank or film and the same geometry, check the dose uniformity. Variations are most likely due to inadequacy of the dose calculation and/or compensator algorithms, but may also be due to errors in constructing the compensator.

9.4.3.18. Photon test 15: Forward planned intensity modulated radiation therapy

Detailed tests to see if the TPS handles forward planned IMRT correctly are beyond the scope of this report. However, some simple tests can show whether a homogeneous dose is predicted and achieved; for example, with a beam incident on a slab phantom at a 30° gantry angle, generate an MLC leaf sequence (or whatever is appropriate to the beam delivery system) to give a uniform dose in a horizontal plane. Export the MLC leaf sequence and, using a water tank or film and the same geometry, check the dose uniformity. Variations are most likely due to inadequacy of the dose calculation and/or leaf sequencing algorithms, but may also be due to errors in beam delivery, for example a poor calibration of the leaf position.

9.4.3.19. Photon issue 1: Inverse planned intensity modulated radiation therapy

See beam issue 1.

9.4.3.20. Photon issue 2: Radiosurgery

See beam issue 2.

9.4.3.21. Photon issue 3: Large field techniques

See beam issue 3.

9.4.4. Electron beam commissioning

9.4.4.1. Issues to be studied

A graded series of checks of various types of electron beam dose calculation, which are described in this section, should be used as guidance for the creation of individualized sets of checks to be used in any particular institution. As this commissioning programme is developed, begin by identifying all the electron beam capabilities that may be put into clinical use with the TPS, and then perform the testing associated with these capabilities. Other capabilities should not be used clinically until they have been confirmed by the user.

The amount and sophistication of testing required for the commissioning of a calculation algorithm depends directly on the number of different capabilities of the TPS system that will be used clinically in the user's institution. This report uses Table 45 to describe the various basic types of capability that may be used in a particular clinic. The user should identify which capabilities listed

in Table 45 are available in the TPS and will be used in the clinic. For this reason a separate table of basic planning techniques requiring verification checks is not presented. Table 45 describes increasing levels of complexity for each case (field shaping, set-up, etc.); these will require additional checks.

For each experiment specified below, the test procedure describes the data and calculation comparisons (i.e. depth dose, profiles, output factor, etc.) needed to compare TPS results and measured data.

9.4.4.2. Test procedures

Most basic electron data have been measured at a 100 cm SSD. Other suggestions for standard electron data set procedures are listed in Table 46.

9.4.4.3. Tests

The following comparisons should be performed and documented in order to assess the accuracy of dose calculations and to document behaviour for clinical analysis of the results.

9.4.4.4. Electron test 1: Square and rectangular fields

Purpose: To check square and rectangular field TPS dose distributions against measured data.

Procedure:

(a) Compare measurements and calculations using 1-D (depth dose and cross-beam profiles) or 2-D dose distributions for square and rectangular fields created with electron applicators and standard inserts.
(b) Check square applicator sizes as used by your machine, for example 6 cm × 6 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, 25 cm × 25 cm (or the maximum field size). Use rectangular applicators, if available.
(c) Measure isodose charts or cross-beam profiles at several depths: for example 0.5 cm, 1 cm, d_{max}, d_{90}, d_{80}, d_{50}, d_{20}, d_{10}, R_p, 5 cm past R_p (where d_{90} is the depth of 90% dose, etc., and R_p is the practical range).

A useful comparison is that of a 2-D plane orthogonal to the central axis (at d_{max}). Tests should be performed using the standard SSD (typically a 100 cm SSD).

TABLE 45. ELECTRON BEAM PLANNING TECHNIQUES REQUIRING VERIFICATION CHECKS

	Level of complexity	Test	Test for each beam
Field shaping	Square and rectangular fields	Electron test 1	Yes
	Shaped apertures	Electron test 2	Yes
	Shielding and skin collimation	Electron test 3	Low energy only
Set-up	SSD dependence	Electron test 4	Yes
Bolus	Slab bolus	Electron test 5	One energy
	Shaped bolus	Electron test 6	Low and high energy
Patient shape	Oblique incidence	Electron test 7	Low and high energy
	Complex surface shapes	Electron test 8	Yes
Inhomogeneities	Bulk	Electron test 9	Yes
	CT based	Electron test 10	Yes
Arcs	Arcs	Electron test 11	Yes

9.4.4.5. Electron test 2: Shaped fields

Purpose: To check shaped field TPS dose distributions against measured data.

Procedure: Use normal electron shaping techniques (such as a low melting point alloy, for example cerrobend inserts in the applicator). These tests are generally beam and algorithm specific. The tests document the limits of clinical use as defined by the user. These limits often change as clinical use evolves. Example configurations can be found in Ref. [74].

Bracket in the following way the range of size, energy, etc., used in the clinic. Measure the central axis percentage depth dose (PDD) and expose films perpendicular to the beam axis at d_{max}. For the following shapes 2 to 5, choose the most clinically relevant energy:

(a) Shape 1: Convex. Generally oval shape, not symmetric. Every energy.
(b) Shape 2: Concave. C shape, central axis under the block. Also measure the PDD in the open part of the field.
(c) Shape 3: Small non-symmetric oval or circle.
(d) Shape 4: Triangular shape, for example 15 cm × 15 cm, with half the field blocked on one side of the diagonal.

TABLE 46. ELECTRON DATA SET PROCEDURES

	Desired	Details
SSD used for basic data	SSD = 100 cm	Use the standard treatment SSD unless recommended otherwise by the TPS vendor
Phantom material	Water	Water phantom should contain full scatter (small water phantoms are suitable only for small field situations)
	Solid water	Solid water is suitable for certain situations if the results obtained in solid water confirm the results obtained in a water phantom; confirm that there are no voids in the solid water
Detectors	Diodes	Electron diodes can be used for most depth dose and profile measurements and typically do not require complex corrections, as ionization chambers do
	Ionization chambers	Parallel-plate chambers are often used for depth dose measurements All ionization chambers require ionization to dose corrections
	Film	Radiographic film for 2-D (orthogonal to beam axis) dose distributions (Kodak XV, ECL or radiochromic film) [70]
	Arrays	Diode arrays can be used An ionization chamber array can be used, with ionization to dose corrections
Beam stability	Stable	Must confirm stability versus time for scanning, which requires long beam-on times

(e) Shape 5: Thin rectangular opening (length close to that of the maximum length in the largest applicator), for example 4 cm × 25 cm (e.g. spinal irradiation).

9.4.4.6. Electron test 3: Surface collimation

Purpose: To check TPS dose distributions for surface collimated fields against measured data.

Procedure: This is a difficult situation for many TPSs. If surface collimation is used in the clinic, planning situations need to be developed for the situations used clinically. Perform a calculation and measurement for a typical situation in which surface collimation is used. Measure the central axis PDD and expose the film orthogonal to the beam axis at d_{max}.

9.4.4.7. Electron test 4: Source to surface distance dependence

Purpose: To quantify the variation in beam characteristics with a changing SSD.

Procedure: Check the following over the broadest range of SSDs allowed clinically. Typically, choose three SSDs, as shown in this example:

(a) Standard SSD (e.g. 100 cm);
(b) Extended SSD (e.g. 105 cm);
(c) Maximum SSD (e.g. 110 cm).

For these SSDs, compare the calculation with measurements:

(1) The depth dose (for each applicator). Note that measurements will depend on the applicator, energy and photon jaw setting for the machine, even if the TPS does not implement applicators.
(2) The output factor (for each applicator).
(3) 2-D isodose charts or at least the profile at d_{max}. Check both the field size and the penumbra. Use a small and large field (applicator) from the above tests.
(4) One shaped field. Check the correct projection, depth dose and profiles. Check both the field size and the penumbra.

See also Section 9.4.5.

9.4.4.8. Electron test 5: Slab bolus

Purpose: To investigate how the TPS handles bolus of constant thickness.

Procedure: Dose calculations for electron beams with bolus depend on both the calculation algorithm and the implementation details. The whole process (including patient set-up, MU calculations and other such details) must therefore be considered.

Several clinical situations (various combinations of SSD and field size) should be tested, comparing the TPS dose distribution with manual calculation of the bolus effect. Check:

(a) The central axis depth dose (relative dose).
(b) The central axis normalization point ($d = d_{max}$) output factor (absolute dose; this check may need to be performed with an MU calculation).
(c) The set-up SSD: does it include bolus?

9.4.4.9. Electron test 6: Shaped bolus

Purpose: To investigate if and how the TPS handles bolus of variable thickness.

Procedure: As with slab bolus, dose calculations for electron beams with bolus depend on both the calculation algorithm and the implementation details. The whole process (including patient set-up, MU calculations and other such details) must therefore be considered.

There are three issues to be checked:

(a) Shaped bolus design tools;
(b) Basic calculation support for shaped bolus;
(c) Confirmation of the actual bolus implementation with a measurement.

(1) If there are specific shaped bolus design tools, create a specific test for these tools.
(2) Test for calculations with shaped bolus. Calculation experiment: add a 30º wedge of unit density bolus to a patient phantom tilted at 30º from the horizontal, to make a perpendicular incidence at 100 cm SSD (i.e. reproduce the standard SSD situation). Compare the isodose distribution with the standard SSD perpendicular incidence result. Compare the MU calculation for the bolus situation with the standard set-up.
(3) Actual bolus check. Create a test case. Use the TPS to design bolus for a phantom, then fabricate it and irradiate the phantom. Confirm the depth dose, profiles and absolute dose.

9.4.4.10. Electron test 7: Oblique incidence

Purpose: To check the agreement between the TPS and the measurement for oblique incidence.

Procedure:

(a) For a standard set-up (e.g. a 100 cm SSD on a flat phantom) with a large (20 cm × 20 cm) field size, measure the 2-D transverse dose distribution for a gantry angle of 30º;
(b) Compare with the TPS calculation.

9.4.4.11. Electron test 8: Complex surface shapes

Purpose: To check the agreement between the TPS calculation and the measurement for a stepped surface.

Procedure: Construct a phantom with, for example, a 2 cm surface step, and compare the calculated dose distribution in a 2-D plane orthogonal to the central axis (at d_{max}) with film measurements.

9.4.4.12. Electron test 9: Bulk density correction

Purpose: To check the agreement between the TPS and benchmark data for a phantom with a slab of different density.

Procedure:

(a) Perform bulk checks versus benchmark (ECWG) data [74] (see the listing in the Annex);
(b) Check the algorithm versus the data;
(c) Calculate lung and bone densities in a slab geometry as well as for a 3-D inhomogeneity (L shape).

9.4.4.13. Electron test 10: Computed tomography based inhomogeneity corrections

Purpose: To check the agreement between the TPS and benchmark data for a CT based calculation using an inhomogeneous phantom.

Procedure: This comparison should be performed using each institution's own density phantom for consistency:

(a) Compare CT based calculations for this phantom with bulk density calculations for the same phantom;
(b) Check for consistency only.

9.4.4.14. Electron test 11: Arc rotations

Few clinics use electron arc rotations and few TPSs support them. However, if they are used, perform (as a minimum) the following tests.

(a) Arc applicator: Usually, electron arcs are performed with a unique electron applicator; the basic characterization of the arc applicator must therefore be performed, similar to that used in electron test 1.
(b) Confirmation of dose distribution: Use measurements in a cylindrical phantom. Perform the arc irradiation. Compare the measured and calculated dose distributions for axial slices (film sandwiched axially in the phantom).

(c) Absolute dose: Use ionization chamber measurements in a cylindrical phantom to confirm delivery of the correct absolute dose for a range of arc angles. This check may include MU calculation and/or manual calculations.

Note that the tests above are a limited set of baseline tests. For clinical use of this technique, a significant number of additional tests are required (off-axis behaviour, variation with changing contours and/or SSD, etc.).

9.4.5. Operational issues

Various operational issues related to dose calculations, such as grid sizes, etc., are also important to the overall accuracy and usefulness of the dose calculation algorithm, and must be checked. The operational checks are summarized in Table 47, and should also be performed by users testing a TPS with only basic planning capabilities.

9.4.5.1. Operational test 1: Algorithm choice

Purpose: To document that routine users will either have only one choice of algorithm for each beam or receive direct feedback about which algorithm is being used for each calculation.

Procedure:

(a) Create single field plans for each different beam and algorithm available for that beam. Note that there may be multiple types of dose calculation algorithm for homogeneous media and multiple types of inhomogeneity correction algorithm implemented for the same beam, so there may be a number of distinct combinations that must be tested. Perform a dose calculation for each combination. Confirm, from the results and messages during the calculation, and other information (including the dose distribution results) provided by the TPS, that the correct dose calculation model has been used in each calculation.

(b) Create a multifield plan that contains a number of beams that use more than one algorithm (if possible). Perform a dose calculation and confirm the correct use of the algorithms and then use the TPS functionality to change the algorithm to the one that will be used for one or more of the beams. Choosing the new algorithm should lead to invalidation of the current calculation results. Perform a new dose calculation. Confirm that for those beams whose algorithm was changed, the new calculation algorithm was used. These checks should be performed with a number of

TABLE 47. OPERATIONAL ISSUES FOR EXTERNAL BEAM ALGORITHMS

	Test	Description
Algorithm choice	Operational test 1	Choose correct algorithm type for each beam
Inhomogeneity corrections	Operational test 2	Are density corrections on or off?
Calculation validity	Operational test 3	If a parameter that affects dose calculation is changed, verify that a new dose calculation is performed
Calculation grid and window	Operational test 4	Changes to the calculation grid or window should force recalculation

different combinations of fields and actions, to identify inappropriate combinations of actions that fail the test.

Note that these checks may not be straightforward for all users to perform.

9.4.5.2. Operational test 2: Inhomogeneity corrections

Purpose: To confirm that the ability to turn inhomogeneity corrections on and off works correctly.

Procedure:

(a) Create a single beam plan with a lung inhomogeneity. Perform the dose calculation with the inhomogeneity correction turned off. Verify that the doses do not show the effects of density corrections.
(b) Turn on the density corrections. Verify that the dose calculation performed earlier is now invalid. Perform the dose calculation and confirm that the calculations are now performed with density corrections.
(c) Repeat the calculation with dose calculations turned off. Confirm that the logic that controls the use of inhomogeneities is working correctly.
(d) For each of the steps, verify that the plan hard copy output correctly documents when the density corrections were on and when they were off.

9.4.5.3. Operational test 3: Calculation validity

Purpose: To confirm that, whenever a parameter relevant to the dose calculations is changed, the current valid dose calculations are set to be invalid and appropriate calculations are performed when necessary.

Procedure: Extensive tests are required to confirm this point, especially if sophisticated calculation validity logic is included in the TPS.

A very limited set of example tests are listed here: this is not a proof. These example tests help illustrate some of the more crucial changes that may cause large problems. An error can depend on which beam is changed, which parameter is changed, where in the application the change is made, the order of the steps the planner performed and many other things. However, these limited tests will illustrate the concept that should be addressed.

Create a multibeam plan with wedges, blocks and an inhomogeneity. Run a set of tests:

(a) Perform the dose calculation.
(b) Make some change (e.g. remove the wedge, modify the block, edit the external contour, change the inhomogeneity, move a beam or some other such crucial aspect of the plan).
(c) Is the calculation invalidated (e.g. the dose distribution should not be displayable any more)?
(d) Perform the new dose calculation and verify that the dose distribution has changed appropriately.
(e) Verify the correct plan output (including the MU calculation).

9.4.5.4. Operational test 4: Calculation grid and window

Purpose: To verify that the TPS functions that set the calculation grids and calculation windows function correctly.

Procedure:

(a) Perform calculations for the same beams but change the calculation window size and/or change the grid size while also changing the grid centre.
(b) Compare the calculation results: they should agree, except for resolution changes due to grid size changes.

9.4.6. Absolute and relative dose

Most TPSs have the ability to calculate and display dose distributions in absolute dose (total dose for the plan or dose/fraction) and in relative dose (per cent of some plan normalization dose). It is extremely important to confirm that all the different ways that dose can be displayed within the TPS work correctly, and that the user understands how to interpret the results. The critical issues include:

(a) Plan normalization and the dose prescription for the plan (Sections 9.4.6.1 and 9.4.6.2);
(b) Calculation of MUs (Section 9.4.6.3).

9.4.6.1. Description of process for beam and plan normalization and monitor unit calculations

There are many different ways that clinics and various TPSs perform plan normalization, beam weighting and MU calculations; detailed descriptions of all methods are therefore inappropriate. However, the basic outline of the process can be described rather generally (see Fig. 15).

Figure 15 shows that there are several distinct steps in the production of a final dose distribution:

(a) Calculate the dose per beam. Firstly, the individual dose distribution from each beam is calculated. At this stage, the dose distribution for each beam is typically the dose relative to some standard weight for the beam.
(b) Beam weighting or beam normalization. The second step is then to multiply these individual beam doses by the beam weight, the relative strength of each beam. For some TPSs this weight is simply a fractional weight (where the total beam weights will add up to 1). For other TPSs this beam weighting may be the MUs to be delivered by each beam. Still other TPSs will use a formal beam normalization step, where the beam weight is defined to be the dose to be delivered by that beam to a specific point, the beam normalization point (this point can be automatically defined (e.g. the point at d_{max} on the central axis or the isocentre of the beam) or it can be chosen by the user).
(c) Summed dose distribution. After the beams are weighted, all the doses (from each beam) are added, resulting in the summed dose distribution. However, before this distribution can be used, it typically needs to be converted to the correct units, scaled or normalized.

(d) Plan normalization. Typically, the summed dose distribution must be converted or scaled or normalized to make it appropriate for display. Often the user wishes to display the dose relative to the dose at some specific point (called the plan normalization point or isodose reference point). This point can be chosen by the user or it can be automatically chosen to be the isocentre of the plan. In addition, the user may choose what dose to display at that plan normalization point. This value, called the plan reference dose, or plan normalization dose, can be quite varied: it can be chosen to be 100%, the absolute dose for the plan (e.g. 60 Gy) or the dose/fraction for the plan, for example 1.8 Gy/fraction, 180 cGy/

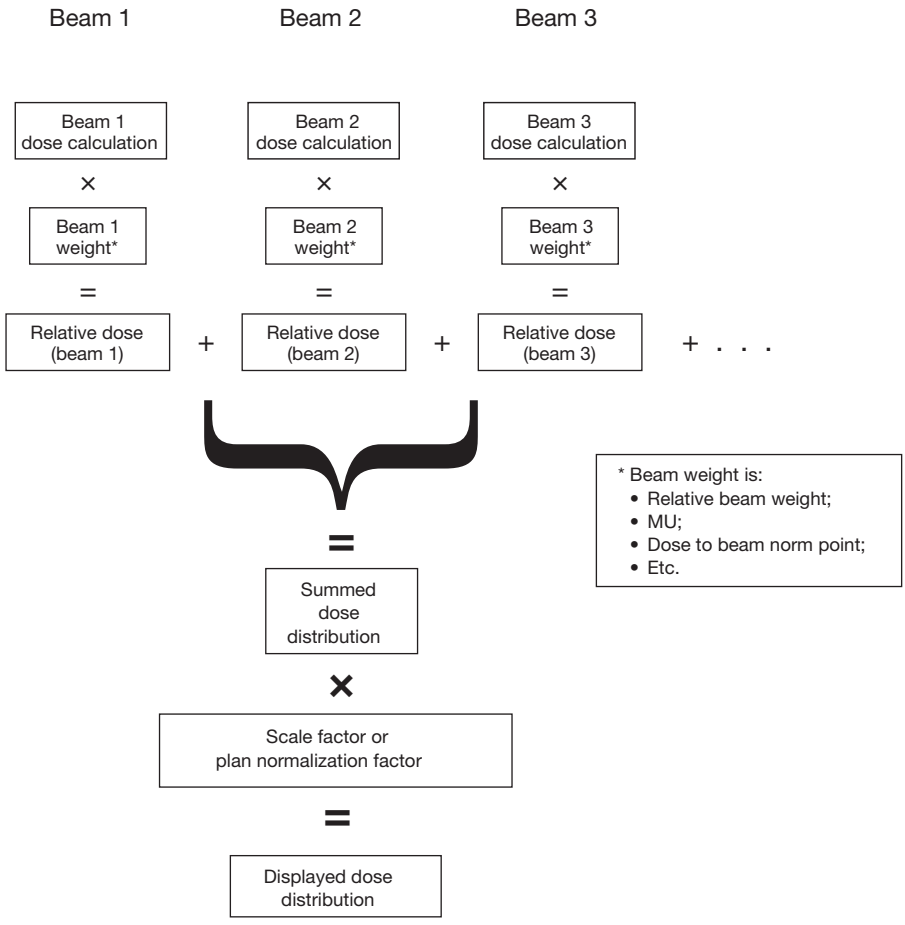

FIG. 15. Beam weighting and plan normalization description.

fraction or any other appropriate value. To normalize the plan, the summed dose distribution is multiplied by the factor F:

$$F = \frac{\text{Plan reference dose}}{\text{Value of the summed dose distribution at the plan normalization point}} \quad (9)$$

(e) MU calculations. Finally, after the displayed dose distribution is completed, MU calculations can be performed (unless the MUs have already been determined within the process). The plan normalization (or scaling) and the beam weighting are critical aspects of the MU calculations, since the goal of the MU calculation is to determine the MU value for each beam that will deliver the dose distribution that has been planned.

9.4.6.2. Dose prescription and plan normalization issues

Quality assurance checks of the TPS functionality involving dose prescriptions and plan normalization are extremely important, since if this capability is not correct the dose displayed for the treatment plan may be wrong. Therefore, all possible methods for plan normalization must be verified. The test below is very general, and must be modified for the specific capabilities of the TPS being tested.

Purpose: To confirm that each plan normalization mode works (and is understood) correctly.

Procedure:

(a) Make a list of the different modes for plan normalization and the different ways that different values of the plan dose can be obtained; for example, normalize the plan to give the following values at the isocentre of the plan: 100%, 60 Gy, 1.8 Gy/fraction, etc.
(b) Create a multifield plan to use for testing. This plan should include shaped fields (with blocks or MLCs) and inhomogeneities (if the user corrects for inhomogeneities).
(c) For each plan normalization mode listed in (a), calculate the dose distribution using the TPS.
(d) Review the shape and location of isodose lines relevant to the plan (e.g. the 100%, 95% and 10% lines) and confirm that the lines are in the same place for each plan normalization.

9.4.6.3. Monitor unit and treatment time calculations

Most external beam treatment planning is performed with a relative normalization of the plan, so that the dose distribution from the plan is described relative to 100% given to some particular point (called the isodose reference point: see above). However, to deliver that plan to the patient, one must determine what dose to deliver from each beam, and then how many machine MUs or the treatment time that the machine needs to deliver to give the appropriate dose to each beam, thereby delivering the overall prescription dose to the prescription point.

A number of important aspects of the treatment planning process affect the way one should calculate the MUs/time to be used to deliver a treatment plan. How these issues are handled and documented in the TPS can affect the MUs/time calculated for a given plan, even if the MU/time calculation is performed within the TPS. Detailed checks of the entire planning and MU/time calculation process should therefore be performed. Table 48 lists some of the relevant issues that should be investigated in detail and briefly describes the types of test that can help to verify the correct behaviour of the entire planning and MU/time calculation process. Users of a TPS with only basic planning capabilities should exclude only those tests related to the use of MLCs.

9.4.6.4. MU test 1: Open fields

Purpose: To confirm the accuracy of the basic MU/time calculation method for open rectangular fields, including the inverse square law.

Procedure:

(a) Create isocentric four field box plans using 5 cm × 5 cm, 30 cm × 30 cm and 10 cm × 30 cm fields on a rectangular phantom.
(b) Calculate the MUs/time required to deliver 2 Gy/fraction to the isocentre of each of the plans, where the beam weights of the AP and PA fields are 0.3 (each) and the lateral fields have beam weights of 0.2.
(c) Perform the manual MU/time calculations and calculations using the TPS plans.
(d) Perform the four field box plan for beams with the standard SSD (100 cm).
(e) Agreement between the manual MUs/time and that obtained by the TPS should be better than 2%.

TABLE 48. ISSUES FOR THE MU/TIME CALCULATION PROCESS

	Issue	Test
Open fields	Basic MU/time calculation Inverse square law	MU test 1
Tangential fields	Missing scatter Contour correction	MU test 2
Wedged fields	Wedge factor Wedge hardness correction Wedge OAR	MU test 3
Blocked fields	Equivalent square method Integration over shape Other method Separate head and phantom scatter	MU test 4
MLC shaped fields	Equivalent square method or integration over shape Does the calculation include jaw effects and a head scatter factor? Small MLC shapes and multisegment IMRT fields	MU test 5
Beam normalization point blocked	When MLCs or blocks shield the beam normalization point, how does beam weighting and MU/time calculation handle this situation?	MU test 4a MU test 5a
Inhomogeneity corrections	How are MU/time calculations performed when inhomogeneity corrections are used in the TPS plan? How are the differences in absolute dose to plan and beam normalization points handled?	MU test 6
Off-axis calculations	What approximations are involved in off-axis calculations?	MU test 7
Dose prescription	How is dose prescription carried from the TPS plan to MU/time calculations? Are there limitations on allowed prescriptions?	MU test 8
Dose distribution units	How do different units used for the display of TPS dose distribution affect the MU/time calculation?	MU test 9
Documentation for the treatment chart	Check that the entire output from the MU/time calculation agrees with the TPS output and machine use	MU issue 1
Clinical check procedure	Verify that the clinical check procedure used for MU/time calculation checks is adequate for the complexity of the plans allowed	MU issue 2

Note: For these test situations, compare the manual MU/time calculation to the MU/time calculation performed using the TPS. MU/time calculations for multiple beam plans are tested in the section on overall clinical tests (Section 9.8).

9.4.6.5. MU test 2: Tangential fields

Purpose: To confirm the accuracy of the basic MU/time calculation method for tangential fields.

Procedure:

(a) Create a tangential fields plan using a square or rectangular phantom.
(b) Place the beam isocentre so that it is near to the corner of the phantom, thereby leaving part of the beams 'flashing' over the edge of the phantom.
(c) Calculate the MUs/time manually and by using the TPS for 10 cm × 20 cm tangential fields.
(d) Compare the manual and TPS MU/time results.

9.4.6.6. MU test 3: Wedged fields

Purpose: To confirm the appropriate use of the wedge factor, wedge hardness correction, wedge off-axis ratio (OAR) and other wedge related aspects of MU/time calculations, using multiple field plans.

Procedure:

(a) Create a three field plan (AP and two laterals) off-centre in a rectangular phantom. Use field sizes of 5 cm × 5 cm, 10 cm × 20 cm and 20 cm × 40 cm (or the largest field size for the wedge). Use different wedges in each field.
(b) Calculate the MUs/time manually and by using the TPS for each of the fields, and compare the results.
(c) Modify the plan to rotate the wedges (changing the field size and depths used for each wedge), calculate the MUs/time manually and by using the TPS, and compare.

9.4.6.7. MU test 4: Blocked fields

Purpose: To identify and check the methods used for MU/time calculations of fields shaped with blocks, including the equivalent square method, algorithms that integrate over the shape of the field and other methods. Check the methods used to separate head and phantom scatter.

Procedure:

(a) Block shapes to be studied should include corner blocks, conformal blocks (completely surrounding a target volume to create an aperture),

complex shaped blocks and any other standard types of shape used in the clinic.

(b) For each of the blocked fields, develop the treatment plan and MU/time calculation in two ways (one of which should include the usual clinical method): (1) by a manual calculation of the MUs/time required for the blocked field using a standard equivalent square methodology; and (2) by using the TPS to take into account all the effects of the blocking. Enter the block shapes using each method normally used in the clinic, for example from the digitizer tablet, using a mouse and BEV and using automated shaping based on a 3-D target volume. Any change in the block entry mode should be confirmed by a test of that method. Confirm that the MUs or time calculated for the fields agree to within a small tolerance (3%) when the two methods are compared.

(c) Document all the methods of TPS and MU/time calculation that could possibly be used for these cases.

9.4.6.8. MU test 4a: Central axis blocked

Purpose: To identify and check the methods used for MU/time calculations when the shaped field includes the shielding of the plan normalization point (or the central axis of the field).

Procedure:

(a) For several example field shapes in which blocks cover the normalization point of the beam, perform a treatment plan and MU/time calculation in two ways (one of which should include the usual clinical method): (1) by a manual calculation of the MUs/time required for the blocked field using a standard equivalent square methodology; and (2) by using the TPS to take into account all the effects of the blocking. Confirm that the MUs or time calculated for the fields agree to within 3% when the two methods are compared.

(b) Document all methods of TPS and manual MU/time calculation that could possibly be used for these cases.

9.4.6.9. MU test 5: Multileaf collimator shaped fields

Purpose: To identify and check the methods used for MU calculations of fields shaped with MLCs, including the equivalent square method, algorithms that integrate over the shape of the field and other methods. Check the methods used to separate head and phantom scatter.

Procedure:

(a) MLC field shapes to be studied should include corner blocking, conformal shaping (completely surrounding a target volume to create an aperture), complex shapes and any other standard types of shape used in the clinic.
(b) For each of the MLC fields, perform a treatment plan and MU calculation in two ways (one of which should include the usual clinical method): (1) by a manual calculation of the MUs required for the shaped field using a standard equivalent square methodology; and (2) by using the TPS to take into account all the effects of the shaping. Enter the field shapes using each method normally used in the clinic, for example from the digitizer tablet, created using a mouse and BEV and using automated shaping based on a 3-D target volume. Any change in entry mode should be confirmed by a test of that method. Confirm that the MUs calculated for the fields agree to within a small tolerance (3%) when the two methods are compared.
(c) Document all methods of TPS and manual MU calculation that could possibly be used for these cases.

9.4.6.10. MU test 5a: Central axis blocked by a multileaf collimator

Purpose: To identify and check the methods used for MU calculations when the shaped field includes the shielding of the plan normalization point (or the central axis of the field).

Procedure:

(a) For several example field shapes in which MLCs cover the normalization point of the beam, perform a treatment plan and MU calculation in two ways (one of which should include the usual clinical method): (1) by a manual calculation of the MUs required for the blocked field using a standard equivalent square methodology; and (2) by using the TPS to take into account all the effects of the blocking. Confirm that the MUs calculated for the fields agree to within a small tolerance (3%) when the two methods are compared.
(b) Document all methods of TPS and manual MU calculation that could possibly be used for these cases.

9.4.6.11. MU test 6: Inhomogeneity corrections

Purpose: To verify the methods used to perform MU/time calculations when inhomogeneity corrections are used in the TPS plan. To determine how

the differences in the absolute dose to plan and beam normalization points are handled and documented.

Procedure:

(a) For a series of phantom based plans with significant inhomogeneities, perform the treatment plan and MU/time calculation with and without density corrections.
(b) Compare both the relative dose distributions and MU/time calculations for the two situations.
(c) Confirm that inhomogeneity effects are handled consistently (i.e. that the combination of TPS and MU/time calculation gives the correct dose to the plan normalization point when inhomogeneities are included).
(d) Document each of the methods that could be used for TPS and MU/time calculation for each of the cases, and confirm that the calculated MUs/time agree to within tolerance. Use each of the available plan normalization methods.

9.4.6.12. MU test 7: Off-axis points

Purpose: To verify the methods used to calculate the dose to off-axis points.

Procedure:

(a) Create a phantom that approximates situations for which off-axis point calculations are needed (e.g. treatment with a mantle field);
(b) Design the test treatment field and define the off-axis calculation point locations;
(c) Perform manual and TPS calculations of the dose to the off-axis points, including MU/time calculations;
(d) Compare the results for off-axis dose point calculations between the two methods;
(e) Repeat the procedure using various field configurations (e.g. long rectangular fields).

9.4.6.13. MU test 8: Dose prescription

Purpose: To confirm the consistent use of the dose prescription between the TPS plan and the MU/time calculation. To determine if there are limitations on allowed prescriptions.

Procedure:

(a) For a series of different situations, define the dose to be prescribed to the plan and then calculate the MUs/time required to deliver the treatment. Confirm that the MUs/time changes appropriately as the prescription changes.
(b) Specify example situations, such as "deliver 50 Gy in 25 fractions to the 95% isodose line for the plan, normalized to the dose at the isocentre". Vary the dose, units (Gy or cGy), number of fractions, isodose line value and any other aspect of the prescription.

9.4.6.14. MU test 9: Dose distribution units

Purpose: To confirm the consistent use of the displayed dose within MU/time calculations, depending on the units chosen for the dose distribution displayed by the TPS.

Procedure:

(a) Choose a multifield plan and vary the way the dose distribution is displayed (in per cent, total dose in Gy, total dose in cGy (if used), dose/fraction in Gy or cGy).
(b) Choose the same prescription isodose line (relative to the plan normalization point).
(c) Calculate the MUs/time required for each field.
(d) Compare the MUs/time for each method: the MUs/time should be constant, independent of the manner in which the dose distribution is represented.

9.4.6.15. MU issue 1: Documentation for the treatment chart

Purpose: To check that all outputs from MU/time calculations agree with the TPS output and machine use.

Procedure:

(a) For each check calculation performed for the tests above (or at least all of the independent methods), confirm that the TPS hard copy output and any entries in the electronic or paper chart used for patient treatment are consistent with the intention of the prescription;
(b) Document the methods for charting and confirm the appropriate training of the clinic staff on how to use and interpret this information.

9.4.6.16. MU issue 2: Clinical monitor unit calculation check procedure

Purpose: To verify that the clinical procedure used for MU/time calculation checks is adequate for the complexity of the plans allowed.

Procedure: As described in the sections on routine QC (Sections 10 and 11), a formal procedure for checking treatment plans and MU/time calculations is crucial for a good ongoing QA programme:

(a) Review the different types of plan and MU/time calculation that are performed and the method used for the implementation of treatment plans on the treatment machines;
(b) Confirm that the procedure used for checking charts, treatment plans and MU/time calculations should catch any of the likely mistakes, transcription errors or other types of error that might be present in any patient's treatment.

9.5. BRACHYTHERAPY COMMISSIONING

9.5.1. General schema for brachytherapy commissioning

9.5.1.1. Basic philosophy

Many of the issues related to external beam commissioning are relevant for brachytherapy. A number of aspects of brachytherapy can be directly compared with analogous aspects of external beam planning (e.g. the description of an external beam's capabilities, location and weight are analogous to the source description for brachytherapy, both types of therapy make use of an anatomical description of the patient and both types of therapy produce a dose distribution that requires tools for display and analysis).

Some additional issues specific to brachytherapy have already been addressed in earlier sections of this report (including descriptions of dose calculation algorithms (Section 4.5) and the source configuration to be entered into the TPS (Section 9.2.11)). This section discusses the testing of system aspects directly related to the dose calculations performed for brachytherapy plans.

9.5.1.2. Methodology for dose calculation commissioning

In principle, the dose calculation algorithms implemented in clinical TPSs are much simpler than those for external beams. They must be flexible enough

to accommodate various radionuclides, various source designs and various techniques. The choice of the proper tables or coefficients, presented in Section 9.2, is of crucial importance for the validity of the results. Most of the reported accidents in brachytherapy treatment planning are the result of inconsistencies between the data or units stored in the tables and the actual characteristics of the sources used clinically (see Table 1). In some situations, specific software is used only for a given type of source or technique. In such a case, it is essential that the software be used only for the situations for which it has been designed. In any case, careful commissioning, as discussed below, is the best safeguard against this major risk of error.

One of the main differences between external beam dose calculation commissioning and brachytherapy commissioning is the fact that, for external beams, it is recommended that the user measure the basic beam characteristics of his or her own treatment machine's beams. This then also forces the user to fit (in some fashion) the dose calculation algorithm so that it does an acceptable job of matching the measured doses. In brachytherapy, there are a very limited number of radiation source types and calculation algorithms, and most TPSs use simple calculation algorithms. Furthermore, the parameters for those simple algorithms are also available for most sources, usually in published scientific articles. This greatly decreases the amount of effort required for commissioning, as well as limits the number of procedures that can be incorrectly performed by an individual user. It is still essential, of course, to confirm the accuracy of all dose calculations that are used clinically, as described below.

9.5.1.3. Creation of the commissioning plan

Creation of the commissioning plan for clinical brachytherapy dose calculations is generally straightforward. Firstly, the user should determine all the clinical brachytherapy procedures that will be used, and generate from that list of procedures all the different types of source and source arrangement that will be used. The reference data for the individual radioactive sources should then be obtained (as described immediately below) for use in the calculation algorithm, as well as for calculation checks. The test procedures (see Sections 9.5.3 and 9.5.4) appropriate to the techniques and sources should then be selected, the tests performed and the results evaluated. Any change in source type, source arrangement or another part of the clinical procedure should be evaluated to see if new (additional) commissioning tests should be performed.

9.5.1.4. Reference data

It is quite difficult to measure accurately the dose distribution around brachytherapy sources. The validity of dose calculations is therefore generally checked by comparison with data in the literature. Note that data in the literature are often obtained with Monte Carlo calculations or may be based on comparisons with other calculations or measurements for a similar type of source. One must therefore be cautious when using these data with other results not included in the literature, since Monte Carlo dose computation for brachytherapy is not trivial and can easily lead to erroneous results. However, for most standard types of source, the published results are used as: (a) input for the parameterization of the TPS dose calculations (Section 9.2.11); and (b) as the reference data for calculation checks.

It is impossible to provide in this report a complete list of all publications that could be used for reference. Some basic references can be found in textbooks such as Refs [89, 90]. In 1995 AAPM TG 43 [54] recommended dosimetric data for ^{192}Ir, ^{125}I and ^{103}Pd. These data still provide a useful reference for comparison and are consistent with the TG 43 formalism (Section 4.5.2). However, since 1995 a number of changes have occurred, including new source designs (e.g. see Ref. [91]) and revision of the air kerma calibration protocols [92, 93]. These changes, which affect mostly low energy emitters (i.e. ^{125}I and ^{103}Pd), must be considered and the individual users must ask the source supplier to provide the reference data and scientific publications corresponding to the source model in clinical use. The source design is less critical for higher energy emitters (i.e. ^{192}Ir, ^{137}Cs, ^{198}Au and ^{60}Co), for which useful references can be found in Ref. [94]. In all cases, the user must ensure that the type of source (radionuclide and mechanical design) is consistent between the one defined for computation and the one actually used for patients [95].

When comparing the TPS dose to reference data, special attention must be given to the source strength for which the reference data were obtained, including the quantity and unit used for strength specification, traceability to a standards laboratory and inclusion or not of self-absorption [96].

9.5.1.5. Dose calculation testing and comparison

Dose calculation testing and comparison is rather straightforward. Dose calculations must be performed with the calculation grid spacing, general source strength definition methods and other calculation parameters within the ranges used for clinical calculations. Calculation with too small a calculation grid, or too large a grid, for example, can lead to misleading results. One should

also perform single source tests, to confirm the basic calculation algorithm, and then perform a number of examples of clinically relevant source arrangements, in order to confirm that the doses from individual sources are added correctly, and to confirm that other implementation problems are not present.

9.5.2. Clinical situations and tests

This section summarizes the testing required for brachytherapy commissioning by listing various common treatment techniques (Section 9.5.2.1) and a number of different ways that algorithms handle brachytherapy issues (Section 9.5.2.2), to help the user define what issues to consider. Tests that should be used for brachytherapy commissioning are then listed, including both dosimetric tests (Section 9.5.3) and geometric tests (Section 9.5.4).

9.5.2.1. Common techniques

There is a wide variety of brachytherapy techniques, as well as a wide variety of radionuclides, that can be used. As with external radiotherapy, the commissioning of brachytherapy calculations can be restricted to the situations that will actually be used in the clinic, provided that whenever clinical practice evolves, commissioning of the new isotope or procedure is undertaken accordingly. Table 49 illustrates a number of techniques and radionuclides in common use throughout the world.

It is clear that, with such a variety, it is impossible to design any detailed commissioning procedure that covers all possibilities. We can, however, describe some basic tests that are essentially common to all techniques. These tests may need to be adapted to particular clinical situations.

For the cases not covered by the tests, we expect that some of the remaining potential problems will be identified when performing the overall clinical tests (see Section 9.8.3), which are, by definition, adapted to the techniques actually implemented.

9.5.2.2. Algorithm related decisions

Whatever technique and radionuclide are used (except for beta emitters, which are not considered here), the dose calculation algorithms are very similar. However, they often have a number of options that may be switched on or off, as illustrated in Table 50.

Before conducting any dosimetric test, it is essential to identify clearly these various options and to decide which will be used in clinical practice. The tests have to be repeated for all options and for all radionuclides used.

TABLE 49. MOST COMMON TECHNIQUES AND RADIONUCLIDES USED FOR BRACHYTHERAPY

	Clinical site	Typical radionuclides	Time and fractionation	Description
LDR intra-cavitary	Mostly gynaecological	^{137}Cs and ^{192}Ir [a]	Continuous, one to several days	Rigid (tubes), flexible (wires) or a series of seeds along a catheter: inserted into intracavitary applicators (sometimes partly shielded)
LDR interstitial	Breast, head, and neck and skin	^{137}Cs and ^{192}Ir [a]	Continuous, one to several days	Rigid (needles), flexible (wires) or a series of seeds along a catheter: inserted into the tissue (or into vectors)
HDR	Intracavitary or intraluminal gynaecology and bronchial tract	^{192}Ir and ^{60}Co	Several fractions, repeated with intervals of up to several days, each fraction lasting some minutes	A single source, stepped along one or several catheters previously fixed into the patient
Pulsed dose rate (PDR)	Gynaecology, breast, and head and neck	^{192}Ir	The full sequence is repeated (typically once every hour); treatment lasts one or several days, aiming at a biological effect comparable with LDR	Single source, stepped along one or several catheters previously inserted into the patient
Permanent implant	Mostly prostate	^{125}I, ^{103}Pd and ^{198}Au	Permanent	Large number of seeds, implanted in tissue (preferably coupled with real time imaging)

TABLE 49. MOST COMMON TECHNIQUES AND RADIONUCLIDES USED FOR BRACHYTHERAPY (cont.)

	Clinical site	Typical radionuclides	Time and fractionation	Description
Plaques	Mostly ophthalmic	^{125}I, ^{106}Ru and ^{90}Sr	The plaque is left close to the tumour (i.e. in contact with external sclera) for several days	Seeds or wires are laid on a rigid plaque, in accordance with a given template; beta emitter plaques are typically not handled by the TPS
Stereotactic implant	Brain	^{192}Ir and ^{125}I	Temporary or permanent	Seeds or wires, stereotactically inserted into the brain
Endo-vascular	Vascular stenosis	^{192}Ir, ^{90}Sr and ^{32}P	Minutes	Gamma or beta emitters inserted into blood vessels; beta emitters are typically not handled by the TPS

[a] Radium-226 is not recommended for clinical use and its use should be discontinued.

9.5.3. Dose calculation tests

To conduct most of the dose calculation tests, it is necessary that the software allow precise definition of the geometrical position both of the sources and of the calculation points. It should also be possible to display (or print out) the corresponding doses. If this is not possible, the tools for geometrical reconstruction could be used to define the position of the sources (see Section 9.5.4), and the printout of the isodose lines in selected planes can be used for dose evaluation, although the results will probably be less accurate. The suggested tests are listed in Table 51. For a TPS with only basic planning capabilities (see Table 25) the user should adapt the list to particular TPS and treatment techniques.

9.5.3.1. Brachytherapy dose test 1: Source description, parameterization and reference data

Clinical situation: All techniques and radionuclides.

TABLE 50. TYPICAL OPTIONS FOR DOSE CALCULATION ALGORITHMS

Option	Comment
Accounting for geometrical distribution of activity (i.e. a line instead of a point)	For sources of small dimensions (seeds) the source can be considered either as a line or as a point (i.e. only the geometrical distance to the centre is used for the inverse square law)
Average anisotropy correction, $\Phi_{an}(r)$	The isodose surfaces around individual (point) sources are spherical, but a correction factor, averaged over all directions α, is included; this approximation is more acceptable if the source orientation is not known; the anisotropy factor could also be averaged over all distances r
Local anisotropy correction, $F(r, \theta)$	A correction for anisotropy (i.e. oblique filtration) is included, depending on the calculation point position relative to the source
Correction for tissue attenuation and scatter	This is normally systematically included (for water) and described by a radial function
Correction for source decay	The dose is reduced if the decay during application is accounted for; conversely, the application time required to reach a prescribed dose is increased if the correction is included
Shielding correction	Depending on the applicator design, some additional corrections can be made available to the user; these may or may not include a (back)scatter modification

Purpose: To ensure that all coefficients and basic data previously entered into the TPS are consistent with the characteristics and dosimetric properties of the sources as used for clinical planning. This test deals with a simplified situation in which the source strength and application time are taken to be equal to unity. It helps to understand the assumptions and limitations of the dose calculation algorithm according to the selected options.

This test must be repeated for each radionuclide and each source design. In the case of a stream of seeds or a stepping source, the source to be considered is one individual seed. In the case of sources of variable length (i.e. iridium wire), one or two typical dimensions should be selected.

Although different formalisms could be used for dose computations, combined with different methods for specifying the source strength (see Section 4.5.2), the methodology remains practically the same.

TABLE 51. BRACHYTHERAPY DOSIMETRIC TESTS

	Issue	Test
Source description	All sources	Brachytherapy dose test 1
Dose rate around a single source	All techniques and radionuclides	Brachytherapy dose test 2
Dose rate for a variable length	Sources of variable length	Brachytherapy dose test 3
Strength decay before application	Existence of a source inventory	Brachytherapy dose test 4
Computation of the treatment time	Time obtained from the TPS software	Brachytherapy dose test 5
Strength decay during application	Short half-life radionuclides	Brachytherapy dose test 6
Dose for a permanent implant	Permanent implants	Brachytherapy dose test 7
Dose for a stepping source	HDR and PDR	Brachytherapy dose test 8
Dose for a source arrangement	All techniques	Brachytherapy dose issue 1
Editing of source characteristics	All techniques and radionuclides	Brachytherapy dose issue 2

Procedure:

(a) Identify the appropriate reference data (scientific publication, data from the source manufacturer, validated data from the TPS vendor, etc.) and make sure that they apply to the sources actually used;
(b) Look for a typical 1-D or 2-D dose distribution and make sure that the associated data are explicitly supplied (see Table 52).

Notes:

(1) Alternatively, build your own reference data by proceeding with a manual dose calculation at various distances from the source using the basic data and algorithms described in Section 4.5. In this case, refer to Table 52 to make sure that the various quantities and units are properly identified.

TABLE 52. CHECKLIST OF DATA ASSOCIATED WITH ANY DOSE DISTRIBUTION AROUND A SOURCE

	Selected option	Comment
Source strength	Air kerma rate, S_k (or K_R) Apparent activity, A_a Contained activity, A_c	Air kerma rate is recommended
Units for source strength	$\mu Gy \cdot h^{-1} \cdot m^2$ (or U) Ci or mCi MBq mg Ra equivalent	The choice of unit is directly related to the quantity above; the use of units of activity or mg Ra equivalent is strongly discouraged
Line source strength	U or U/cm MBq or MBq/cm	For line sources it is common that the strength is specified per length unit (see also brachytherapy dose test 2)
Value of the corresponding strength	Unity Other (10 or 100 or…)	It could be useful to use a large strength value to increase the number of significant digits on the printout
Filtration characteristics	mm Pt Transmission coefficient	This is important if the strength is expressed as contained activity (not recommended)
Unit for dose (or dose rate)	Gy, Gy/h or Gy/day cGy, cGy/h or cGy/day	For total dose, the application time must be known; the unit must be clearly printed out
Unit for distances (if table)	cm or mm (x, y) Reduced co-ordinates (i, j) Polar co-ordinates (r, θ)	Sometimes the distances are expressed relative to the source dimensions
Axis or plane position relative to the source	Origin at the centre of the source Other?	Confirm isotropic distribution if 1-D data are used (1-D $\rightarrow$ 3-D); in principle, for 2-D data the plane contains the source axis and a symmetry is expected in the dose distribution (2-D $\rightarrow$ 3-D)
Underlying assumptions (or selected options) for dose evaluation	See Table 50	If some assumptions are made or simplifications are performed, this should be known, in order to interpret correctly the comparison with the TPS dose distribution

(2) Use Table 52 as a template to review the quantities and units that will be used in clinical practice. Make sure that they are supported by the TPS. If not, you can decide either to change your local practice or to ask for a modification of the TPS software.

9.5.3.2. Brachytherapy dose test 2: Dose distribution from a single source

Procedure:

(a) Define in the TPS a source with the same characteristics as a typical source to be used clinically. If necessary, adjust the strength value to make it equivalent to the strength of the source for which the reference dose distribution is available. If the source characteristics (particularly the source strength) are defined in an inventory (see Section 9.2), use the same date for application as for the reference date of the inventory (see also brachytherapy dose test 3). Compute the dose rate (preferably per hour for LDR or per minute for HDR) at some selected points that can also be obtained from the reference data. These points could be at various distances and positions from the source.

(b) As an example, if the source axis is along the y axis and its centre is at the origin, compute the dose at the following points (depending on the reference data):
   (i) $y = z = 0$ and $x = 1, 2, 5$ and 10 cm;
   (ii) $y = x = 0$ and $z = 5$ cm (expected to give the same result as $y = z = 0$ and $x = 5$ cm);
   (iii) $z = 0$, $y = L/2$ and $x = 1, 2$ and 5 cm (where L is the length of the source);
   (iv) $x = z = 0$ and $y = 1, 2, 5$ and 10 cm (skipping points where $y < L/2$).

(c) Compare the calculated dose rate with the reference data for the same points. The difference should not exceed 5%.

(d) Plot the isodose lines in planes such as x–y, y–z and z–x and make sure that the unit is clearly printed out and that these plots are consistent with the numerical values previously found.

Notes:

(1) To be meaningful, the calculated dose must show a number of digits corresponding to an accuracy of around 1% (typically at least three significant digits). If this is not the case, one can change the strength (i.e. multiply by 10 and divide the resulting dose rate by 10) to obtain a better resolution. Do not change the application time (which should remain

small compared with the radionuclide half-life) to avoid changes in the decay correction (see brachytherapy dose test 4).

(2) If there is no correction for anisotropy, the isodose surfaces are expected to become practically spherical at a distance from the source larger than three times its maximum dimension. The diameter of such a sphere can be easily calculated manually, assuming all activity is concentrated at the centre of the source and by taking into account the inverse square law and the radial function (as explained in Section 4.5). As a first approximation, the radial function can be ignored in order to check the order of magnitude.

(3) If the TPS algorithm is based on an average anisotropy correction, discrepancies larger than 5% can be found, especially along the source axis ($x = z = 0$). Such local discrepancies are generally acceptable.

(4) If a systematic discrepancy (typically less than 10%) is found and remains unclear, it is likely to be due to the conversion factor from 'strength' to dose (i.e. dose rate constant). If this factor cannot be changed, it is possible to systematically correct the strength of the clinical sources, as given to the TPS, in order to include the corresponding correction. This would be the case if the strength of the source is expressed as contained activity (A_c) or mg Ra equivalent and if there is no self-absorption correction in the software. However, this practice is not recommended. Users are urged to discontinue the use of such quantities and to use consistent quantities throughout the process.

9.5.3.3. Brachytherapy dose test 3: Dose rate for a variable length

Clinical situation: Sources of variable length (i.e. iridium wires or a stream of seeds).

Purpose: To check how the dose distribution changes according to the length of the source.

Procedure:

(a) Compute the dose distribution around a single source (a line or seed), as described in brachytherapy dose test 1. Keep the same source strength and application time and change the length by a given factor (i.e. ×2 or ×5). For a stream of seeds, define as many seeds as needed to reach the required equivalent length.

(b) Compute the dose at reference points and display isodose lines in selected planes.

(c) Compare the dose before and after the change in length.

(d) Check if the dose at large distances (i.e. two or three times the source length) is approximately multiplied by the same factor as the source length. If this is the case, it confirms that the strength is expressed per unit length (U/cm) for lines or per seed (U) for streams. Make sure that this is consistent with the specification of the clinical sources. If the dose at distant points does not change much with length, it implies that the strength is assigned to the line as a whole, and this should be clearly recognized.

9.5.3.4. Brachytherapy dose test 4: Correction for source strength decay before application

Clinical situation: The strength used as input to the TPS usually has to be recalculated manually at the starting time of the application. This is evident for radionuclides with short half-lives (several days) that are regularly supplied, but it must not be forgotten for radionuclides such as ^{137}Cs (with a half-life of 30 years), which are kept in use for many years. In such cases, it is the user's responsibility to update at regular intervals (e.g. every six months) the strength values to be used.

Alternatively, the TPS software could make use of an inventory, where the original strength of the source at a reference date is given (see Section 9.2). Brachytherapy dose test 4 is applicable only for this situation.

Purpose: To check that the source strength is correctly recalculated and used, as a function of the current date of application.

Procedure:

(a) Compute the dose at a point (e.g. for the configuration of brachytherapy dose test 1) and record carefully the reference strength and date (which should be the same as the starting date of the application);
(b) Change the date of the application, making it, for example, one half-life later than the reference date;
(c) Check that the calculated dose rate is changed accordingly (i.e. divided by two if one additional half-life is used).

Notes:

(1) Make sure that the convention for date input is clearly understood. Note that the US convention is often different from the European convention (i.e. 12 January 2001 would be written as 01/12/01 in the USA and 12/01/01 in Europe). In case of doubt try to use a month number larger than 12. Check also software protection that prevents inconsistent date input.

(2) It is recommended that this test be repeated after each change of the inventory.

9.5.3.5. Brachytherapy dose test 5: Computation of treatment time

Clinical situation: For any TPS software that computes the treatment time.

Purpose: To check the validity of the algorithm for computation of the application time.

Procedure: Use the distribution computed in brachytherapy dose test 2 as the prescription and check that the resulting manual calculation of time agrees with the TPS computation (see also brachytherapy dose test 6).

9.5.3.6. Brachytherapy dose test 6: Correction for source strength decay during application

Clinical situation: This test is meaningful only for radionuclides with a short half-life relative to the application time (e.g. ^{192}Ir, ^{125}I and ^{103}Pd). It is not significant for half-lives longer than one year (e.g. ^{137}Cs, ^{60}Co and ^{226}Ra) or for HDR.

Purpose: To check if a correction is applied to the dose distribution and/or the treatment time and to account for the source decay during the application (provided that the corresponding option is selected).

Procedure:

(a) Compute the dose at a point (e.g. for the configuration of brachytherapy dose test 2) for two different application times t_1 and t_2, expressed as a fraction of the radionuclide half-life T: $t_1 = k_1 \times T$ and $t_2 = k_2 \times T$. Record the corresponding doses D_1 and D_2.
(b) Compute the ratio D_1/D_2 and, depending on the choice of k_1 and k_2, compare the result with the value found in Table 53.

If the software is designed to compute the application time for a given reference dose, proceed with the following: use the dose distribution computed in step (a) with the larger application time, and consider it to be the prescription (i.e. D_1 at the reference point). Compute the corresponding application time and check that it is equal to the time used in step (a) (i.e. t_1) and larger than the time calculated without decay correction (i.e. D_1 divided by the initial dose rate at the reference point).

TABLE 53. SUGGESTED VALUES AND CORRESPONDING RESULTS TO TEST THE DECAY CORRECTION DURING THE APPLICATION

k_1	0.1	0.2	0.5	2
k_2	0.05	0.1	0.1	1
k_1/k_2 (= D_1/D_2 without decay correction)	2	2	5	2
Expected D_1/D_2 [a] (with decay correction)	1.97	1.93	4.37	1.50
Decay correction factor	–2%	–3%	–13%	–25%

[a] $D_1/D_2 = (1 - \exp(-0.693 \times k_1))/(1 - \exp(-0.693 \times k_2))$.

9.5.3.7. Brachytherapy dose test 7: Dose integration for a permanent implant

Clinical situation: Reserved for permanent implants (e.g. prostate).

Purpose: To check the dose computation when sources are not removed from the patient.

Procedure:

(a) Compute the dose distribution around a permanent source, as described in brachytherapy dose test 2 (note that usually, for dedicated software, the application time is not to be specified and is assumed to be infinite).
(b) Identify clearly the dose units of the reference dose (dose rate) distribution (generally Gy/h or cGy/h) and make sure that the corresponding time t_{ref} is less than 1% of the radionuclide half-life T.
(c) Correct the reference dose distribution by applying a dimensionless multiplication factor equal to $1.44 \times T/t_{ref}$. The resulting dose distribution should be the same as the computed one.

9.5.3.8. Brachytherapy dose test 8: Dose distribution for a stepping source

Clinical situation: Stepping sources as used in HDR or PDR and optimization procedures.

Purpose: Check that the computed dwell times and source positions are consistent with the computed dose distribution. The dwell times and positions are generally automatically generated by the TPS software to match a given dose prescription.

Procedure:

(a) Use a reference dose distribution, such as that described in brachytherapy dose test 2, as the dose prescription.

(b) Compute the corresponding source positions and dwell times. The positions and times should be consistent with the reference dose distribution.

Note that this test could be difficult to conduct, depending on the software specificity. However, a rough check of the consistency can be made by comparing the doses at large distances, where the geometry has little influence (see note 2 of brachytherapy dose test 2), and assuming that the stepping source is equivalent to a single source of the same activity, located at the geometrical centre of all source positions and left for a time equal to the sum of the individual dwell times.

9.5.3.9. Brachytherapy dose issue 1: Dose distribution around the source arrangement (and applicators)

Clinical situation: Any technique.

Purpose: To check that the contributions from several sources are accounted for. The mutual influence of the sources (attenuation) is generally ignored and is not tested. If the applicators are shielded and if the software takes this into account, that fact should be recognized but no test procedures are suggested, except a qualitative review of the computed dose distribution and consistency of the dose modification with expected attenuation.

Procedure: Duplicate the source used in brachytherapy dose test 2 and check that the dose is doubled. This does not validate the computation of the geometrical factors, which is covered by brachytherapy dose test 3.

9.5.3.10. Brachytherapy dose issue 2: Changing options and editing of source characteristics

Clinical situation: Any radionuclide and technique.

Purpose: To check that the dose distribution is updated when dose calculation options and/or source characteristics are modified. To make sure that the plan identification is modified accordingly.

Procedure:

(a) Start from a configuration such as that used in brachytherapy dose test 2. Individually change each option likely to be used and each source characteristic (radionuclide, source strength, application time, position, etc.) and check that these changes are reflected immediately in the dose distribution.
(b) Observe which plan identification is printed out on the various sheets (version or variation number, time stamp, etc.) to make an unambiguous

association between the list of the selected options, the source characteristics and the plots of the dose distributions.

(c) Make sure that this identification appears on all relevant documents.

9.5.4. Geometrical tests

9.5.4.1. Methods for source reconstruction

In the previous dosimetric tests it has been assumed that the position of the sources was known accurately. In clinical practice, the sources are located in the patient and their position has to be calculated from a 3-D geometrical reconstruction based on a series of (at least two) 2-D images. The exception is the case in which the sources are rigidly fixed at known positions to some kind of applicator (i.e. ophthalmic plaques). This is referred to as the template situation.

Knowledge of the dose distribution around a source arrangement is useful to give dimensions of the isodose surfaces. It would be sufficient for assessment of the quality of a brachytherapy plan if it is assumed that the sources have an appropriate location in relation to the target volume. However, it is recommended, and becoming more common, to relate the source position to anatomical structures (target volume and critical organs). Several levels of anatomical description are possible. Practically all methods of source reconstruction enable dose calculation at some specific anatomical points, but only methods based on a series of slices (CT, MRI and ultrasound) allow for a full 3-D reconstruction of anatomical structures similar to the methods used for external beams. The main methods used for source reconstruction are listed in Table 54.

The quality of the source reconstruction is important for the accuracy of the dose calculation. For a point source, the dose variation behaves according to the inverse square of the distance to the calculation point; for example, a 1 mm error on a 1 cm separation between two point sources results in a 20% error in the dose at mid-distance.

9.5.4.2. Tests for source reconstruction

It is impracticable to describe a methodology that covers all clinical situations and methods for source reconstruction. It is common that a reconstruction algorithm that works satisfactorily and accurately for a number of sample cases fails for some clinical source arrangements. Table 55 presents some examples of tests that should be conducted at the commissioning stage. These tests are also illustrative of what should be considered for clinical plans

TABLE 54. MAIN METHODS USED FOR GEOMETRICAL SOURCE RECONSTRUCTION

	Description	Issue
Template	The sources are rigidly attached to an applicator	Source positions can be entered from the keyboard or recalled from a predefined table Should be complemented by some other method if the dose to anatomical structures is to be computed
Stereoshift films	Two films are taken with two positions of the X ray source shifted parallel to the films	The shift distance must be large enough and known accurately for a precise reconstruction of the sources Anatomical structures can be reconstructed if they consist of visible, well defined landmarks
Orthogonal films	Two films are taken from orthogonal points of view	The use of a frame with fiducial embedded markers improves the accuracy of source reconstruction Anatomical structures can be reconstructed if they consist of visible, well defined landmarks
CT based reconstruction	A series of thin adjacent parallel slices is used for 3-D reconstruction	Images can be transferred directly to the TPS (see Section 9.3) Intersections of the sources can be automatically detected or easily identified Depending on the slice thickness, the co-ordinates of the source extremities could be reconstructed inaccurately
MRI or ultrasound reconstruction	As for CT reconstruction but based on MRI or ultrasound slices	Risk of distortion Difficult to identify accurately the source intersections Gives useful information on anatomical structures Could be combined with CT

for individual patients. Users of a TPS with only basic planning capabilities should omit the last two tests in Table 55.

9.5.4.3. Brachytherapy geometry test 1: Quality of the geometrical reconstruction

Reconstruction method: All methods except templates.

TABLE 55. TESTS FOR GEOMETRICAL RECONSTRUCTION OF BRACHYTHERAPY SOURCES

	Issue	Test
Quality of reconstruction	All methods except templates	Brachytherapy geometry test 1
Manual source identification	All methods except templates	Brachytherapy geometry test 2
Automatic source identification	All methods with automatic identification	Brachytherapy geometry test 3
Total versus active length	Cases in which part of the source is inactive	Brachytherapy geometry test 4

Purpose: To check that the basic data and algorithm used for the geometrical reconstruction of sources are accurate enough for clinical planning.

Procedure:

(a) Use a phantom of known geometry, representative of the dimensions used clinically and containing radio-opaque markers (and/or wires). In most cases this phantom can be designed easily by the TPS user from simple objects (i.e. wood or plastic objects containing markers that are either embedded or glued onto the surface).
(b) Proceed with the radiological procedure and source reconstruction as they would be performed clinically.
(c) Examine the software output (graphical output, printed out co-ordinates, etc.) to obtain geometrical information such as consistency of the reconstruction (general shape), distances between markers and lengths of wires.
(d) Compare the reconstructed and actual geometry. The difference should not exceed 1 mm for short distances (<2 cm) and 2 mm for longer distances.

Notes:

(1) The acceptable tolerance could be slightly greater if the phantom has not been designed with a geometrical accuracy better than 1 mm.
(2) For line sources (rectilinear or curved wires), it is very useful to compare the expected length with the reconstructed length.

9.5.4.4. Brachytherapy geometry test 2: Source identification (manual)

Reconstruction method: All methods in which the sources have to be identified manually on each image used for reconstruction.

Purpose: To identify and reduce the risk of erroneous reconstruction following an incorrect assignment of the source images shown on the various views.

Procedure:

(a) Use a phantom and a radiological procedure such as that described in brachytherapy geometry test 1;
(b) Intentionally mix the identification of several of the sources shown on the images;
(c) Proceed with the reconstruction;
(d) Observe if any software protection or warning is activated;
(e) Examine the output (numerical and graphical) to establish how this type of error would be detected in clinical practice (see also the note under brachytherapy geometry test 3).

9.5.4.5. Brachytherapy geometry test 3: Source identification (automatic)

Reconstruction method: All methods in which the sources are automatically identified on images used for reconstruction.

Purpose: To check that the algorithm used for source identification works properly.

Procedure:

(a) Use a phantom and a radiological procedure such as that described in brachytherapy geometry test 1;
(b) Proceed with automatic identification and reconstruction;
(c) Examine the output (numerical and graphical) to check that there is no error in source identification and/or reconstruction.

Note that this test could be difficult and meaningless using a phantom. It would make sense to use clinical cases, in which the quality of the images could be very different from that for a phantom. However, it is more important to realize that such identification algorithms could fail. Depending on the systems, some tools may be provided to help in assessing the quality of identification and/or reconstruction. However, most often it is up to the user to accept or reject a reconstruction after careful examination of the graphical output.

9.5.4.6. Brachytherapy geometry test 4: Total versus active length

Reconstruction method: All cases in which the length of the actual or dummy source as seen on radiological images differs from the active length.

Purpose: To check how the software differentiates between the total and active length.

Procedure:

(a) Use a phantom and a radiological procedure such as that described in brachytherapy geometry test 1 or design a specific phantom with a single dummy source of known length.
(b) Depending on the software, define the source as being active only for part of its length. Prepare another plan with the same source being active along its full length.
(c) For both plans, proceed with source reconstruction and dose computation, preferably in a plane containing the source.
(d) Check the numerical outputs to compare the expected and calculated total length (and active length if printed out).
(e) Compare the isodose lines for the two plans and check that the changes correspond to the change in active length.

9.6. PLAN EVALUATION TOOLS

Plan evaluation tools vary widely among different TPSs, from the straightforward use of isodose curves on 2-D contours to DVHs, NTCPs and 3-D isodose surfaces. Since plan evaluation tools are the main way in which the results of the planning are communicated to the physician and treatment planner, QA testing of these capabilities is very important.

The tests in this section illustrate again that performing QA tests during commissioning can reveal any problems or errors in how the plan evaluation information from the TPS is interpreted within the clinic.

9.6.1. Dose display

Table 56 summarizes some dose display issues that should be included for testing by users of a TPS with only basic planning capabilities.

TABLE 56. DOSE DISPLAY ISSUES

	Issue	Test
Plan normalization	Correct representation of absolute and relative dose	Dose display test 1
Isodose lines and surfaces	Correct interpolations (2-D and 3-D)	Dose display test 2
Cold and hot spots	Correct automated display of hot spots (maximum dose) or cold spots	Dose display test 3
Relevant points	Point dose agreement with isodose lines and surfaces	Dose display test 4

9.6.1.1. Dose display test 1: Plan normalization

Purpose: To confirm the correct dose display with different plan normalization types.

Procedure:

(a) For standard clinical cases calculate the dose distribution and display isodose lines or surfaces in axial, sagittal, coronal and/or 3-D display modes;
(b) Mark (in some fashion) the location of various isodose lines and/or surfaces;
(c) Transform the plan normalization (e.g. from per cent dose to total dose) so that, for example, the 100% dose becomes 60 Gy;
(d) Confirm the correct location of the new total dose lines relative to the earlier display;
(e) Test each variation of the plan normalization modes for the system.

9.6.1.2. Dose display test 2: Isodose lines and surfaces

Purpose: To verify that the various displays of isodose surfaces and isodose lines agree.

Procedure:

(a) Calculate the 3-D dose distribution for standard plans;
(b) Construct combined displays of various geometries (e.g. multiple slices, orthogonal planes and planes within 3-D volumes);

(c) Confirm the consistency of the dose displayed.

9.6.1.3. Dose display test 3: Cold and hot spots

Purpose: If the system is able to automatically determine or document the maximum dose to the plan, or other such information, to confirm that the system does this correctly.

Procedure: The test method depends on the capabilities of the system. In general, verify the accuracy of the maximum dose region for a number of different plan types.

9.6.1.4. Dose display test 4: Point dose display

Purpose: To confirm the consistency of point dose displays with other displays.

Procedure: Same as dose display test 3. Perform tests to confirm agreement.

9.6.2. Dose–volume histograms

Current state of the art TPSs use DVHs to summarize the distribution of the dose to particular organs or other structures of interest. Table 57 summarizes the various issues.

Notes:

(a) Test artifacts. Especially for grid based calculations of the volume inside structures; regular geometric shapes can deceive as they are sensitive to grid based aliasing and other problems. It is possible to have large percentage errors in a volume calculation (used for a DVH) when performing the calculation with simple test objects that are rectangular or cubic.
(b) Not all TPSs support all of the DVH functionality tested in this section; for example, the bin size may not be user selectable: of course, that test would then be omitted, but it is important to understand how a particular system is calculating DVHs, so that any limitations can be recognized. Aim to determine bin size, sampling frequency, etc., from the supplied documentation or by requesting the information from the vendor.

TABLE 57. DOSE–VOLUME HISTOGRAM ISSUES

	Issue	Test
Type	Direct, cumulative and differential DVHs	DVH test 1
Plan normalization	Correct normalization of plans and individual beams	DVH test 2
Relative and absolute dose	Absolute versus relative comparisons	DVH test 3
Volume determination	Volume determination	DVH test 4
Histogram dose bin size	Histograms with different dose bin sizes can give different results	DVH test 5
Structures	Identifying, excluding and including different structures into the histogrammed volume	DVH test 6
Consistency	Consistency between DVH and the isodose display	DVH test 7
Calculation of grid size and points distribution	Geometric resolution	DVH test 8
DVH comparison guidelines	Guidelines for comparisons of DVHs between plans and/or patients	DVH test 9
Dose statistics	Test statistics such as minimum dose, maximum dose, mean dose, volume statistics, etc.	DVH test 10

9.6.2.1. DVH test 1: Types of dose–volume histogram

Purpose: To check the capability to create DVHs of different types (e.g. direct, cumulative or differential). To check self-consistency between the different types.

Procedure:

(a) Create a simple phantom case with simple test structures of known volume (both target and normal structure types). An example is a patient with a simple central target volume, such as a cube.
(b) Calculate the dose distribution of a simple and easily understood plan within the test structures. Two examples are a four field box and a single wedged field. If the TPS system permits, form the direct, cumulative and differential DVHs (each DVH displaying the same basic data, but in different formats (see Section 4.4.4)).

(c) Verify that the three DVHs each coincide with the calculated dose distribution.
(d) Make a hard copy output and confirm the consistency of the hard copy with the displayed DVHs.

9.6.2.2. DVH test 2: Plan normalization

Purpose: To ensure that the DVHs agree with the dose distribution as the type of plan normalization changes.

Procedure:

(a) Use a simple test anatomy and plan (as in DVH test 1);
(b) Calculate the dose distribution of a simple plan with an easily understood dose distribution within the test structures;
(c) If the TPS permits, for each type of plan normalization (typically plans are normalized to 100% at the isocentre, to total dose, for example 50 Gy at the isocentre, to daily dose, for example 2 Gy/fraction), form the direct, cumulative and differential DVHs;
(d) Verify that the DVHs each coincide with the calculated dose distribution as normalized;
(e) If the plan normalization can be changed without recalculation of the dose distribution, perform these changes, then regenerate the DVHs and reconfirm their accuracy;
(f) Make DVH printouts to confirm that the appropriate dose display is maintained in the hard copy output.

9.6.2.3. DVH test 3: Relative and absolute dose comparisons

Purpose: DVHs can often be displayed in either relative or absolute dose (on the horizontal axis), even if the plan has been calculated with some other type of plan normalization. Confirm that the DVH calculations, based on either relative or absolute dose methods, perform correctly.

Procedure:

(a) Use the same simple test case (anatomy with a simple target volume) and four field box plan (DVH test 1);
(b) If the TPS permits, change the DVH display between the relative dose (100%) and absolute dose (total dose prescription or dose per fraction);
(c) Confirm the consistency of the display;
(d) Make a printout and confirm consistency.

9.6.2.4. DVH test 4: Relative and absolute volume

Purpose: The volume axis of any DVH can be plotted either as relative volume (per cent of the volume of the structure being analysed) or as absolute volume (by multiplying the per cent volume by the calculated total volume of the structure). To verify that conversion between these modes is correct.

Procedure: A number of different structures must be studied, since the volume calculation performed for the DVH calculation can be sensitive to a number of factors, including size, shape of the structure, method (random points or grid based), etc.

(a) Create a number of structures of varying size and shape (not all square);
(b) Calculate the volume of these structures by an independent method;
(c) Compare the absolute DVH volume of the entire structure with the independent calculation;
(d) If the TPS permits, convert the DVH to a relative volume display (per cent volume);
(e) Compare the absolute and relative volume DVHs and confirm self-consistency;
(f) Make a printout of each DVH and confirm that the output is still correct.

Note that special phantoms are available to aid such volume determinations [15].

9.6.2.5. DVH test 5: Histogram dose bin size

Purpose: The dose bin size of the histogram is an important parameter. Dose binning is frequently performed to calculate the differential DVH, which is then integrated to derive the cumulative form. If the DVH is calculated as a dose–volume distribution, where the dose values are simply ranked and distributed at a regular interval, binning is unnecessary for the cumulative form. It is then used only for derivation of the differential form. In all cases, if the bin size is too large, the results could be inaccurate and the DVHs would no longer be able to be compared.

Procedure:

(a) If the TPS permits, for the simple test phantom above (DVH test 1), perform DVH calculations for at least two different bin widths (one a multiple of the other);
(b) Perform a comparison of the resulting DVHs in direct, cumulative and differential formats;

(c) Confirm by a manual calculation that the direct and cumulative DVHs for the two calculations agree;
(d) Compare the differential DVHs and confirm that they are in agreement.

9.6.2.6. DVH test 6: Compound structures

Purpose: To confirm that flexibility in the use of structures within the DVH functionality works correctly. In particular, to check the ability to define compound structures using Boolean logic (R_Lung + L_Lung, Liver-Target, etc.).

Procedure: The ability to define compound structures is dependent on the capabilities of the TPS. Typical functions include the ability to:

(a) Create Struct1 OR Struct2, which is the voxels contained within Struct1 or Struct2;
(b) Create Struct1–Struct2, which is the volume that is contained within Struct1 but is not within Struct2;
(c) Create Struct1 AND Struct2, which is the volume that is included within the overlap between Struct1 and Struct2, and other such combinations.

For each capability, perform the following test:

(1) Create a test phantom with several known 3-D structure volumes, some of which overlap each other (e.g. target and normal structures that overlap).
(2) Create separate structures matching the composite (OR), minus and overlap (AND) regions.
(3) Implement a simple multibeam plan that gives simple dose distributions to the identified structures, and perform the 3-D dose calculations.
(4) Create the chosen composite structure and perform the DVH calculation.
(5) Compare the DVH with the DVH for the corresponding outlined structure to confirm that the correct DVH is formed. Comparisons of absolute volumes of the compound structures can be helpful in confirming that the correct voxels are formed for the DVH.

9.6.2.7. DVH test 7: Consistency with dose display

Purpose: Since it is often difficult to analyse the consistency between a DVH and the displayed dose distribution, owing to differences in calculation and display methods, to confirm that the two methods of representing the same dose distribution are correct.

Procedure: Confirmation of the consistency between the displayed dose distribution and the DVH depends on the dose calculation grid, the isodose surface display method (or isodose curve display if 2-D methods are used), the DVH calculation grid, the DVH dose bin resolution, the dose display resolution and other such factors. The details of the test method must therefore be adjusted to account for these factors.

The general principle is to create a dose distribution within a structure in which the dose gradient, the minimum and/or the maximum dose can be controlled and checked both on the dose display and on the DVH [97]; for example, one can create a very conformal plan (a plan in which the 95% isodose surface conforms tightly to the target volume). Calculate the DVH for the target volume, and then use whatever 2-D or 3-D dose display capabilities are available to compare the 95% isodose surface with the displayed target volume. If the minimum dose to the DVH of the target volume is 95%, then the 95% isodose surface should just cover the target volume, while displaying the 96% isodose surface should allow some parts of the target volume surface to protrude from the dose surface.

However, interpretation of the results of these types of display test involves paying attention to the factors listed above: dose bin resolution in the DVH, geometrical resolution versus the resolution of the dose calculation grid and the dose display grid, and other such factors. It is important to investigate discrepancies between the two types of analysis and to understand the error bars on both the dose display and on the DVH capabilities.

9.6.2.8. DVH test 8: Calculation point sampling

Purpose: To document and understand the geometric resolution of the DVH and dose calculation processes.

Procedure:

(a) Use the same plan as used for DVH test 7.
(b) Perform the dose calculation with different calculation grid sizes or a different number of random points, calculate the DVHs and compare.
(c) If the TPS permits, choose different resolutions of the DVH anatomy (grid or density of points), perform different DVH calculations and compare.

Analyse differences in behaviour to determine the sensitivity of the DVH results to the choice of grid position and/or resolution of sampling. This analysis should be performed both for high and low dose gradient regions.

9.6.2.9. DVH test 9: Dose–volume histogram comparison guidelines

Purpose: To describe or delineate guidelines for the interpretation of DVHs.

Procedure: The precision or resolution with which a DVH describes the calculated dose distribution depends on:

(a) The geometric resolution of points (random points or grid points) at which the dose is evaluated, and potentially on the grid (which may be different) on which the dose was originally calculated;
(b) The dose bin size with which the histogram is calculated;
(c) How the DVH code handles issues such as voxels that are partly in one structure and partly in another, or other similar situations.

In order to understand the error bars that result in a DVH due to some of these effects, the user should make a number of comparisons. If the TPS permits, for a given dose distribution and set of structures of interest, calculate the DVH for each structure based on changing densities of points and with different dose bin sizes. The clinically used bin size can then be chosen, based on the level of expectation of the physicians who interpret the DVHs against the bin size. The DVHs obtained for different densities of points, both for the total volume of each structure and for the dose representation, can be compared, allowing general rules for the expected resolution of information from the DVHs to be established. These calculations should be performed for small, large and convoluted (complex shaped) structures.

9.6.2.10. DVH test 10: Dose and volume statistics

Purpose: To confirm accurate calculations of dose statistics (minimum, mean or maximum dose) and volume statistics (total volume, V_{05} (volume receiving 5% dose or less), $V_{60\text{Gy}}$ (volume receiving 60 Gy or more), etc.).

Procedure:

(a) Create well behaved dose distributions using combinations of simple opposed and wedged fields (or other simple combinations);
(b) Calculate the dose statistics of interest using the DVH software and confirm with manual analysis of the dose distribution (somewhat tedious but straightforward);
(c) For the different point sampling methods described in DVH test 9, estimate the potential errors in these values.

9.6.3. Biological effects

Many TPSs now incorporate biological effect issues into the plan evaluation tools. Among these are knowledge of dose/fraction, and possibly the calculation of the biological effective dose (BED) or any of a number of similar entities, and the use of models such as Lyman's NTCP [51, 52] and various TCP models [49]. While these can be useful, it should be noted that the quantitative result cannot be checked in the same way as a physical value such as dose or distance. The objective of the tests is to ensure that the TPS gives results consistent with the model it claims to be using.

9.6.3.1. Bioeffect test 1: Normal tissue complication probabilities

The most commonly used bioeffect evaluation tool is the Lyman NTCP model (or other similar models). This model depends on:

(a) The DVH of the structure to be evaluated;
(b) The NTCP model parameters for this structure;
(c) The actual calculation code used to generate the NTCP value.

Purpose: To verify the behaviour and results of the NTCP model calculation.

Procedure:

(1) Verify the input model parameters for each structure to be modelled;
(2) Create or obtain a clinical or clinically relevant shape for each structure of interest;
(3) Create plans that deliver relatively uniform doses to the structure;
(4) For a number of different plan prescription values of increasing dose, generate the DVH for the structures and then calculate the NTCP for each structure;
(5) For each result, verify that the calculated values of the NTCP agree with the expected values for such a uniform irradiation (this could be done with a manual calculation of the NTCP assuming a uniform dose is delivered to the structure).

9.6.3.2. Bioeffect test 2: Tumour control probabilities

For TCP model calculations, repeat bioeffect test 1, modified to check the calculated TCP values for the target volumes.

9.6.3.3. Bioeffect test 3: Fractionation and other biological effect results

If the linear–quadratic model or any other biologically related model is involved in clinical treatment planning, design and perform tests to confirm the behaviour of the results or corrections over the range of clinical use.

9.7. PLAN OUTPUT AND DATA TRANSFER

Output of the treatment planning information and transfer of that information to the patient chart and/or the treatment machine is an important aspect of the planning and delivery process that requires appropriate QA. Correct transfer is critical because any error or misinterpretation of information transferred from the TPS to the therapy machine (or chart) will result in a systematic error in all the treatment fractions that are delivered.

Two general methods exist by which this transfer is accomplished: (a) manual transfer, in which the plan parameters are transcribed manually from the TPS output into a chart (paper or electronic) or a machine control system; or (b) automated transfer from the TPS into the machine control system or other automated delivery system (DICOM-RT is an example of this). For the manual transfer system, QA checks must account for the significant random errors that may occur with manual transcription, as well as the possibility of systematic errors or misinterpretation of TPS information. For the automated transfer methods, most errors will be systematic. Unfortunately, the automated nature of the transfer can create a false trust. Some types of systematic error can be very difficult to detect. Clearly, careful QA for both types of process is important.

Each site should maintain a standard protocol for the downloading of TPS information into the machine control system, including an audit trail system that can document who performed which transfers, as a way of ensuring that the appropriate plan information is being transferred to the machine. This protocol must also ensure that any unexpected behaviour during the transfer is investigated, documented and resolved.

9.7.1. Plan output

The hard copy plan output must include details of all the relevant parameters involved in the creation of the treatment plan, as well as any other information necessary to interpret these parameters. The information required by AAPM TG 53 [18] (Table 58) is a good summary of what should be part of the output. A check of the plan output should include one or more test plans.

TABLE 58. HARD COPY OUTPUT REQUIREMENTS, MODIFIED FROM AAPM TG 53, TABLE 3-21 [18]

	Comment
Text printout	Software version
	Patient identification (name, registration number, etc.)
	Identification of the source of anatomical data (i.e. CT examination number and date, etc.)
	Treatment machine, modality and energy for each beam
	Beam parameters (e.g. field size and gantry angle) in machine specific co-ordinates for each beam
	Isocentre location in 3-D for each beam
	Set-up SSD (or SAD and depth) for each beam
	Presence and orientation of beam modifiers (e.g. blocks, wedges, compensators and bolus) for each beam
	Calculation algorithm used
	Whether inhomogeneity corrections were used, and the source of the inhomogeneous description of the patient
	Dose calculation grid size
	Dose to and position of calculation points
	Plan normalization
	MUs/time (not calculated by all systems)
	How to convert the plan's beam weights into MU/time calculations (for systems that do not calculate MUs/time)
	Plan and beam version numbers, time and date of calculation
	User comments
2-D dose plot	Location and orientation of displayed plane
	Scale factor
	Intersection of fields (with fields labelled)
	Presence and proper orientation of beam modifiers
	Patient contour and grey scale information
	Dose information (e.g. isodose lines)
	Location of calculation points
BEV or DRR	SSD or SAD
	Scale factor
	Associated field
	View orientation
	Collimation, including block shapes and/or MLC aperture
	Patient anatomical information
	Central axis location

TABLE 58. HARD COPY OUTPUT REQUIREMENTS, MODIFIED FROM AAPM TG 53, TABLE 3-21 [18] (cont.)

	Comment
DVH	Plot legend Scales and units Case, plan and other identifying information Associated anatomical structures
3-D display	Scale factor View orientations Beam locations and orientations Anatomy and dose identification Isodose surfaces

It is important that any individual printed document (text or graphics) is unambiguously labelled regarding:

(a) Patient identification;
(b) Machine identification;
(c) Plan identification (number, date and time).

This is the only way to ensure that separate documents belong to the same plan.

9.7.2. Standard plan transfer issues

For both manual and automated transfers, the basic issues are the same. Each parameter in the TPS that determines how the treatments will be performed must be transferred to the patient chart (electronic or paper) and/or the machine control system. Commissioning of the plan transfer process must confirm that the correct information is transferred from the TPS to the machine chart, as listed in Table 59. The list of tests in Table 59 may be reduced by users of a TPS with only basic planning capabilities according to the non-availability of specific options (MLCs, compensators, etc.).

Notes:

(a) Virtually all the tests below must be performed for each machine and beam to be used.

TABLE 59. PLAN TRANSFER ISSUES

	Issue	Test
TPS co-ordinates and scaling	The TPS may use its own co-ordinates and scaling system or it may represent machine parameters according to the machine's system	Transfer test 1
Machine co-ordinates and scaling convention	What co-ordinates and scaling system are used for each treatment machine? Are they consistent with the TPS?	Transfer test 2
Angle co-ordinates	Correct default position and direction defined?	Transfer test 3
Table co-ordinates	Absolute or relative moves, direction, resolution, units and scale	Transfer test 4
Collimators (jaws)	X ray jaws and field sizes	Transfer test 5
Machine description	Overall machine definition	Transfer test 6
Machine motions	Machine capabilities, motion speed and limitations	Transfer test 7
Wedges	Wedge definitions, labels and directions	Transfer test 8
Blocks	Blocks' tray labels and other parameters	Transfer test 9
MLC	MLC file labels, leaf definitions and labels	Transfer test 10
Electron applicators	Applicator used and jaw positions	Transfer test 11
Uniqueness	Department, machine and beam labelling	Transfer test 12
Miscellaneous devices	Compensators and bolus	Transfer test 13
Dose prescription	Dose and MU/time information	Transfer test 14
Brachytherapy	Source position and dwell times	Transfer test 15

(b) Many of these tests can be combined into a number of plans that are transferred and then analysed.

9.7.2.1. Transfer test 1: Treatment planning system co-ordinates and scales

Purpose: To determine if the TPS represents machine co-ordinates and scales with its own system or with a machine specific system.

Procedure:

(a) Read the TPS documentation;
(b) Determine if the motion readings (e.g. the gantry angle) are always represented the same way in the TPS or if such values are displayed using

a machine specific scaling system that can be modified to agree with the physical machine.

9.7.2.2. Transfer test 2: Co-ordinate and scale conventions for the treatment planning system and equipment

Purpose: To confirm the general co-ordinate and scale convention to be used for the TPS and/or equipment.

Procedure:

(a) Determine the general convention (e.g. IEC) used for each machine to be modelled.
(b) Determine if the TPS has allowed the general convention to be set correctly for each modelled machine. The convention should also be compared with the simulator conventions.

9.7.2.3. Transfer test 3: Angle readings

Purpose: To confirm the accuracy of the transfer for each angle reading.

Procedure:

(a) For the gantry angle, collimator angle, table angles and any other angle type parameter, confirm that the following features are handled correctly: zero position (e.g. gantry pointed downwards), direction (clockwise or counterclockwise), and units and resolution (degrees, tens of degrees).
(b) Use sample plans with a number of fields that check the entire range of angles allowed, transfer the plans to the machine and confirm that the position of the machine agrees with the TPS representation.

9.7.2.4. Transfer test 4: Table co-ordinates

Purpose: To confirm the accuracy of the transfer for each table co-ordinate.

Procedure:

(a) The table motion (if handled within the TPS) may be defined absolutely or relatively (with respect to some reference point), and may be based on a non-linear scale (e.g. IEC).
(b) For the table x, y, z, confirm that the following features are handled correctly: zero position (e.g. centred at the isocentre), direction, units (mm or cm) and resolution.

(c) Use sample plans with a number of fields that check the entire range of table motion allowed, transfer the plans to the machine and confirm that the position of the machine agrees with the TPS representation.

9.7.2.5. Transfer test 5: Jaws

Purpose: To confirm the transfer of field size and jaw position information.

Procedure:

(a) Create plans to verify the entire range of jaw positions, including small fields, large fields, the use of *x* asymmetric jaws, the use of *y* asymmetric jaws and the use of *x* and *y* asymmetric jaws;
(b) Transfer each plan to the machine;
(c) Confirm the correct jaw position.

9.7.2.6. Transfer test 6: Machine definition

Purpose: To confirm the agreement of the machine's description used in the TPS with the parameters of the treatment machine.

Procedure: For each parameter in the database description of each machine entered into the TPS, confirm the accuracy of each parameter. Examples include the isocentre distance of the machine, the location at which field sizes are defined and the machine configuration (MLC yes/no, jaw motions allowed, etc.). This should be performed also for an SSD value different from the machine SAD and for a collimator rotation different from zero.

9.7.2.7. Transfer test 7: Machine motion

Purpose: To confirm the accurate transfer of machine data from the TPS.

Procedure: Some TPS representations of machines contain knowledge of machine motion capabilities, for example motion limits and speeds. For each such parameter, confirm that the TPS parameterization agrees with the machine capability. Create plans to test the transfer limits. These may include:

(a) Gantry angle: minimum, maximum, resolution and speed.
(b) Collimator angle: minimum, maximum, resolution and speed.
(c) Table angle: minimum, maximum, resolution and speed.
(d) Table *x*, *y*, *z*: minimum, maximum, resolution and speed.

9.7.2.8. Transfer test 8: Wedges

Purpose: To confirm the accurate transfer of each wedge.

Procedure: Most treatment machines are equipped with one or more wedges, and include a dynamic (virtual) wedge (moving jaw) capability.

(a) Create plans that make use of each wedge, in each direction of use that is allowed, and transfer to the machine, recording carefully the collimator rotation being used.
(b) Confirm that the wedge is placed in the correct orientation on the machine. The use of dynamic wedges or automatic wedges (inside the head of the machine) may require a dosimetric check to confirm that the correct wedged dose distribution is generated by the machine. Also confirm that fields too large for each wedge are not allowed by the TPS and cannot be transferred to the machine.
(c) Confirm that the wedge identification (codes, etc.) is also correct.

9.7.2.9. Transfer test 9: Blocks

Purpose: To confirm the accurate transfer of blocks from the TPS to the block cutter and/or treatment machine.

Procedure: Blocks are created manually from BEV plots of the block shape, from blocks drawn on simulator films or by automated machines that accept transferred block shapes. For the methods used in the institution, create a number of test plans, including a number of block shapes, for example asymmetric simple blocks (to check directionality), conformal blocks and very complex block shapes to check the accuracy and resolution of the block creation process.

(a) Transfer the block shapes from the TPS, fabricate the blocks, install on the block tray and test them on the machine;
(b) Irradiate a film in air (i.e. with little or no overlying buildup, to give a sharp image), placed at the isocentric distance, with the central axis and cross-hairs noted on the film (for alignment);
(c) Determine the shape irradiated from the film, and confirm the accuracy of the block creation process;
(d) If the block tray identification codes are available, confirm the behaviour of the identification system for each of the test blocks.

9.7.2.10. Transfer test 10: Multileaf collimators

Purpose: To confirm the transfer of MLC parameters to machines.
Procedure:

(a) For each machine with an MLC, create a number of MLC shapes, including small and large fields, and a variety of shapes, including very asymmetrically placed apertures (to check the across midline behaviour).
(b) Transfer each shape to the machine.
(c) Confirm the correct co-ordinates inside the machine control system.
(d) Irradiate each field with a film in air at the isocentric distance.
(e) Determine the irradiated shape from the film and confirm agreement with the planned shape. Some MLC systems have limitations, for example a prohibition against interdigitation or a limited opening between leaves. For each limit, confirm that the TPS prohibits the disallowed behaviour or that the transfer process flags inappropriate instructions and assists the user in resolving the problem.

9.7.2.11. Transfer test 11: Electron applicators

Purpose: To confirm the accurate transfer of each electron applicator.
Procedure: Most treatment machines are equipped with one or more electron applicators.

(a) Create plans that make use of each applicator (if the TPS permits) and energy, and transfer to the machine;
(b) Confirm that the applicator and X ray jaw positions are set correctly.

9.7.2.12. Transfer test 12: Uniqueness

Purpose: To confirm that all the parameters defined for a machine, beam or other device are unique.
Procedure:

(a) Create a series of plans in the TPS that exercise all functionality of the description of the machine, for each machine.
(b) Transfer all plans to the appropriate machine.
(c) Confirm that there are no ambiguous issues during the transfer; each different type of block used, each different type of wedge and each type of compensator must be checked.

9.7.2.13. Transfer test 13: Miscellaneous devices

Purpose: To check other devices.
Procedure:

(a) For any other devices modelled within the TPS, for example compensators and bolus, create test cases for each device that check the limits of its capabilities;
(b) Transfer each to the treatment machine and confirm that all relevant parameters are set correctly.

9.7.2.14. Transfer test 14: Dose prescription

Purpose: To confirm the accurate transfer of dose and MU information.
Procedure:

(a) Create test plans for a series of normal treatment protocols, with their usual dose prescriptions.
(b) Transfer these plans to the appropriate treatment machines, including all dose and prescription information.
(c) Confirm the accurate incorporation of that information into the machine control system record (or chart) for treatments. Checks should include daily fraction dose, number of fractions, prescription point, prescription total dose, MUs/time, treatment delivery backup timer and other relevant information. Test cases with wedge filters should be included.

9.7.2.15. Transfer test 15: Brachytherapy

Purpose: To verify that source positions or source dwell times as determined by the TPS are correctly transferred to the brachytherapy device, and that the sequence can be delivered as planned.

Procedure: This test is described in general terms only. The specifics depend strongly on the specific TPS, brachytherapy devices in the department and available method of transfer.

(a) For a range of examples, as appropriate to clinical use, transfer the planned source arrangement to the delivery device. This could be a manual transfer, as for an LDR unit, in which a sequence of active and inert pellets is entered via the unit's control panel. It could also be an automated transfer (as for some LDR units and most HDR units), in

which removable electronic media or network transfer is used to program the device.

(b) Verify that the device accepts the correct pattern and is capable of executing it without error. This could be done by comparing the hard copy from the TPS with the hard copy from or display on the brachytherapy unit.

(c) Check that the plan is compatible by delivering (HDR) or commencing (LDR) a dummy treatment.

Note that the verification of the actual dose delivered is not covered by this test. It depends on a range of factors relating to treatment delivery, such as the applicator geometry and speed of source movement, and also requires specialized measuring techniques. This certainly needs to be considered during brachytherapy commissioning, but is beyond the scope of this report.

9.7.2.16. Transfer issue 1: Additional safety requirements

Automated plan transfer between the TPS and a machine or delivery information system can greatly reduce the random errors usually associated with transcription of information. However, there is a greater possibility of systematic errors than in using the more manual methods, and hence QA for the electronic system must be modified to enhance its integrity and accuracy. Related issues include:

(a) Computer and network security and integrity (Section 6).

(b) Periodic testing of transfer (Section 10). As part of commissioning, a subset of test cases from Section 9.7.2 should be used as test cases for the periodic testing of the transfer.

9.8. OVERALL CLINICAL TESTS

In the previous sections, detailed descriptions have been given of procedures and tests that should be performed to commission and verify various specific subcomponents of the TPS. Before starting clinical use, it is important that a number of tests be performed that are typical of clinical treatment procedures, including both the dose distribution calculation and the MU/time calculation. A subset of these clinical commissioning tests can then be used for reproducibility tests as part of the ongoing QA process. For commissioning, these tests should be performed for phantom situations such that direct measurements can be made at one or more selected points within the phantom.

For external beams, these checks are primarily aimed at confirming that the absolute dose delivered to the phantom will be correct as determined by measurement. Thus the measurements will be performed with detectors such as a calibrated ionization chamber or calibrated thermoluminescent dosimeters that can determine absolute dose. They can be performed either on a single beam basis or for multifield techniques. Table 60 summarizes the types of clinical test that should be considered for this purpose. Users of a TPS with only basic planning capabilities should perform only tests related to a real clinical application of the radiation treatment at the hospital.

For brachytherapy, the aim is to check the whole process and to compare the actual dose distribution with that expected. Since absolute dose measurement is somewhat difficult, it could be replaced by an independent evaluation of the expected dose based on manual calculation and/or table look-up.

Purpose:

(a) To take a specific clinical situation through the total planning process;
(b) To perform the actual dose delivery;
(c) To confirm that the absolute dose delivered is within the expected tolerance.

Procedure (external beams):

(1) Enter a phantom description into the TPS.
(2) Enter beams into the TPS.
(3) Calculate the prescribed treatment plan: deliver 2 Gy to the prescription point.
(4) Calculate the MUs/time to deliver the plan.
(5) Deliver the plan to the phantom while making measurements as described.
(6) Analyse the measured dose versus expected dose.
(7) Decide whether the agreement is within tolerance.

It is not necessary that all these tests be performed, since the types of test that are implemented should be dependent on how the system is used in a particular clinic. However, at the minimum, a subset should be considered and perhaps additional tests should be added, depending on which types of equipment there are in the department and on which types of treatment technique are implemented. Thus departments using only basic treatment techniques should perform checks of simple plans. If CT scanning or CT simulation is used, then this process should also be assessed. For institutions using IMRT, a full IMRT plan should be developed and tested.

TABLE 60. EXAMPLE CLINICAL TESTS EVALUATING THE TOTAL TREATMENT PLANNING PROCESS

	Description	Test
Open fields	Four field box and open fields	Clinical test 1
Blocking	Same four field box and heavily corner blocked fields	Clinical test 2
Wedges	Wedge pair	Clinical test 3
CT planning	AP–PA plan treating inhomogeneity (anthropomorphic or plastic phantom)	Clinical test 4
Conformally shaped fields	Six field axial conformal prostate plan	Clinical test 5
Non-axial or non-coplanar fields	Conformal non-coplanar brain plan	Clinical test 6
Electrons	Combined photon–electron plan	Clinical test 7
Brachytherapy applicator	Gynaecological: tandem and ovoids	Clinical test 8
Multiplanar implant	Two plane breast implant	Clinical test 9
Volume implant	Prostate implant	Clinical test 10
HDR	HDR test case	Clinical test 11

For each of the suggested tests, some type of measurement or manual dose evaluation of the final dose delivery should be performed, to ensure that the correct absolute dose would be delivered to the patient following the completion of the total treatment planning process.

The following are some example plans that could be considered. While it is not necessary to implement these particular examples, it is very important that some typical situations be developed and tested right through to the evaluation of absolute dose. This is especially true for a new TPS. For software changes, only a subset of these tests need to be performed.

9.8.1. Clinical test 1: Open four field box

A four field box is an extension of a two field parallel pair. A rectangular phantom can be used. The AP–PA separation should be about 20–25 cm and the lateral separation should be about 30 cm. A typical prescription of 2.00 Gy per fraction should be used. MUs (or time for ^{60}Co) should be calculated. A measurement should be performed in the phantom at the prescription point, with either a calibrated ionization chamber or a calibrated thermoluminescent

dosimeter. The agreement of the absolute dose intended versus the measured dose should be within 2% (or within the accuracy capabilities of the detector used).

9.8.2. Clinical test 2: Same four field box, heavily corner blocked

This is the same as clinical test 1, but significant blocking should be used in the field corners, possibly with a partial central block if this is ever performed in the institution. Section 1 described a very significant series of errors that occurred in Panama [6]. It was this technique with heavily blocked fields that resulted in errors in time calculations by nearly a factor of 2 (i.e. patients received nearly double the prescribed dose).

9.8.3. Clinical test 3: Wedge pair

To test the accuracy of wedge calculations, especially with respect to MUs or time, a pair of two coaxial beams with wedges can be placed on a rectangular or parallelepiped phantom. Again, a measurement should be made at the reference point shown and an absolute dose of 2.00 Gy should be delivered.

9.8.4. Clinical test 4: Computed tomography plan

Perform a simple plan using CT data with, for example, a four field box technique on a pelvic image. Ideally, this would be done on an anthropomorphic phantom, and corresponding measurements should be performed in the phantom for a typical dose prescription (e.g. 2.00 Gy). Alternatively, the rectangular phantom of clinical test 1 could be used and the same results should be obtained as in clinical test 1.

9.8.5. Clinical test 5: Multiple field coplanar conformal prostate plan

For those departments performing 3-D CRT, a plan that is typical for the department should be assessed. Ideally, this would be done on an anthropomorphic phantom with contour corrections and shaped fields typical of the clinical situation. Thus if a low melting point alloy is used clinically, this should also be used for this test case. If MLCs are used, these should be applied for this test case. If a six field technique is typical for the department, this is the technique that should be used. Alternatively, the standard conformal technique for the department should be assessed. Again, the usual dose per fraction should be delivered. This is especially important for six or more field techniques in which the dose per field will be quite small. The measurement should be performed at the prescription point.

9.8.6. Clinical test 6: Conformal non-coplanar brain plan

If non-coplanar fields are used, these also should be tested; for example, a non-coplanar technique is often used to treat the pituitary with two lateral fields and one anterior oblique vertex field. This could be tested on a rectangular phantom with wedges for the lateral fields, including an appropriate collimator rotation and an oblique vertex type field. Again, calculations and measurements should be performed using a typical dose per fraction. The phantom should be CT scanned if this is how the patients' treatments are planned.

9.8.7. Clinical test 7: Combined photon–electron plan

When both electrons and photons are used in combination, it is useful to generate a plan combing 50% photons with 50% electrons at a given specification point; for example, if the combined plans include 6 MV photons and 9 MeV electrons, a depth of 1.5 cm can be chosen for the prescription point. A dose of 1.00 Gy with photons and 1.00 Gy with electrons can be delivered at a depth of 1.5 cm, and the measurement can be performed in the phantom at the same depth.

Sometimes chest walls are treated with both photons and electrons, but each at a different reference depth. In this case two fields might be placed side by side with an appropriate gap. The relative dose distribution can be measured using film dosimetry (remembering to account for the appropriate non-linearity with dose, as is usually done with film dosimetry). The important factor here is to assess the dosimetry across the two fields to ensure that the computer is performing the relative weightings correctly and that it is handling the dose in the junction sufficiently well.

9.8.8. Clinical test 8: Gynaecological application

A typical gynaecological treatment using an intra-uterine applicator (tandem) and two intravaginal applicators (ovoids or colpostats) could be used. The source locations should be verified using a phantom and/or by superimposition with radiographs (after correction for magnification). The dose calculations can be verified by using an independent simplified manual calculation applying, for example, the Patterson–Parker system for linear sources [98].

9.8.9. Clinical test 9: Two plane breast implant

Create a two plane breast boost implant. Verify source identification and the location, dose calculations, dose prescriptions and plan evaluation.

9.8.10. Clinical test 10: Iodine-125 prostate implant

Create a volumetric ^{125}I implant (e.g. for the prostate). Verify source identification and the location, dose calculations, dose prescription and plan evaluation.

9.8.11. Clinical test 11: High dose rate or pulsed dose rate test case

The following should be tested for HDR afterloaders:

(a) Definition of the source trajectory.
(b) Verification that the optimization and dwell time algorithms work correctly.
(c) Output of source position–dwell time data.
(d) Transfer of source position–dwell time data to the afterloader machine.
(e) Special calculation model for the HDR source.
(f) Special recommissioning requirements for routine source changes; ensure that the source strength changes between patient treatment fractions are implemented correctly.

10. PERIODIC QUALITY ASSURANCE

10.1. INTRODUCTION

QA does not end once the TPS has been commissioned. It is essential that an ongoing QA programme be maintained. The programme must be practicable (i.e. it must be structured in such a way that the risk of a serious error in patient dose is minimized), but not so elaborate that it imposes an unrealistic commitment on resources and time.

Periodic checks of the integrity of hardware, software and data transfer should be carried out. The QA programme needs to be flexible enough to adapt to change. Procedures should be established to cover software upgrades, changes to peripheral devices, methods of data transfer and modifications to beam data. Training of staff, system management and security are also very important aspects of QA.

10.2. TREATMENT PLANNING SYSTEM

Various QC checks are listed in this section (Table 61), together with a reference to a test designed to perform each check and a suggested frequency of the test. Some of the tests are not applicable to TPSs with only basic planning capabilities, and the user should adjust the list in accordance with the features of the TPS.

10.2.1. QC test 1: Central processing unit

Purpose: To check that the CPU, memory, file systems and operating system are functioning optimally.

Procedure:

(a) Restart or reboot the computer as recommended by the vendor or as appropriate (UNIX based systems in particular can benefit from such a reboot);
(b) Observe onscreen messages during the reboot, to detect possible system malfunctions.

10.2.2. QC test 2: Digitizer

Purpose: To check that the digitizer sensitivity has not drifted.

Procedure:

(a) Input a contour of known dimensions into the TPS in the normal way.
(b) Use a screen ruler to verify the correct dimensions. Agreement within 0.2 cm is reasonable.

10.2.3. QC test 3: Plotter

Purpose: To check that the plotter scaling has not drifted.

Procedure:

(a) Plot the contour from QC test 2.
(b) Check the size against the input and previous plots. Agreement within 0.2 cm is reasonable.

TABLE 61. EXAMPLE QUALITY CONTROL CHECKS AND CORRESPONDING FREQUENCIES

	Test	PS	W	M	Q	A	U
Hardware							
CPU	QC test 1			Yes			Yes
Digitizer	QC test 2		Yes[a]	Yes[b]			Yes
Plotter	QC test 3				Yes		Yes
Backup recovery	QC test 4				Yes		Yes
Anatomical information							
CT (or other) scan transfer	QC test 5	Yes					Yes
CT geometry and density check	QC test 6				Yes		Yes
Patient anatomy	QC test 7	Yes					Yes
External beam software (for photons and electrons)							
Revalidation (including MUs/time)	QC test 8	Yes				Yes	Yes
MUs/time	QC test 9	Yes					
Plan details	QC test 10	Yes		Yes			
Electronic plan transfer	QC test 11	Yes		Yes		Yes	Yes
Brachytherapy							
Revalidation	QC test 12					Yes	Yes
Plan details	QC test 13	Yes					
Independent dose and time check	QC test 14	Yes					
Electronic plan transfer	QC test 15	Yes		Yes		Yes	Yes
TPS software recommissioning	Section 10.3						

PS: patient specific (Section 11); W: weekly; M: monthly; Q: quarterly; A: annually; U: after software or hardware update.

[a] Sonic digitizer.

[b] Electromagnetic digitizer.

10.2.4. QC test 4: Backup recovery

Purpose: To confirm that data that have been backed up can be recovered.

Procedure:

(a) Restore data that have been recently backed up (without overwriting current data).
(b) Check the integrity of the restored data. Depending on the TPS's backup utility, a separate procedure may be necessary for patient data, beam data and executables.

10.2.5. QC test 5: Computed tomography transfer

Purpose: To check that CT transfer protocols have not changed.

Procedure: Transfer four basic patient studies (prone, supine, head first and feet first). This can be done either on a phantom or on a patient with appropriate markers on the left, right, superior and inferior sides. If these tests are not done routinely, take extra patient labelling precautions (e.g. left–right, superior–inferior) for patients scanned by non-standard CT protocols (see Section 11.7).

10.2.6. QC test 6: Computed tomography density and geometry

Purpose: To check that the relationship between the CT number and density and image geometry has not changed.

Procedure: This test is similar to anatomy test 9 in Section 9.3.3:

(a) Scan a phantom using a standard protocol (at least a single slice with known density inserts and geometry).
(b) Transfer the images to the TPS, use the TPS tools to measure densities and distances. Agreement within 0.2 cm is reasonable for distances. Agreement within 0.02 is reasonable for relative electron densities (i.e. CT numbers for a given object should not vary by more than ±20). If a significant change in the CT number is observed and cannot be eliminated by recalibration of the CT scanner, new CT number to electron density data need to be entered into the TPS. If CT data are input using film, geometric checks for scaling and distortion are necessary. Distortion may arise from either the CT filming process or the digitization process.

(c) Produce a film of the test phantom, making sure that the image contrast (level and window) is as before.
(d) Input the film in the usual way (e.g. by using a charge coupling device (CCD) camera or digital scanner). If the film digitization is used for inhomogeneity corrections, bulk densities are usually assigned manually (see Ref. [99] for average lung densities). If the TPS automatically maps the digital matrix to densities, check that the densities are correct.

10.2.7. QC test 7: Patient anatomy

Purpose: To check that patient anatomy representation has not changed.
Procedure:

(a) Use the same phantom as for anatomy test 2 in Section 9.3.3.
(b) Repeat anatomy tests 2 and 3 in Section 9.3.3. For anatomy test 3, check for precise agreement with the commissioning tests. Overlaying hard copy is the easiest way, provided that QC test 3 has been performed first. Agreement within 0.2 cm is reasonable.

10.2.8. QC test 8: External beam revalidation

Purpose: To check the constancy of external beam dose calculations to safeguard against inadvertent alteration or corruption.

Procedure: A check sum of all the data files will show whether any files have changed. If this cannot be done, an alternative is to review the directory that contains the data. Check the creation dates of files to ensure that none have been inadvertently altered. If the input data have been parameterized or processed, it is the most recent data that must be checked. The raw data are of secondary importance, although they also should be maintained. The data can usually be scrutinized directly. Display and print the TPS configuration and calculation model parameters and check against the commissioning data.

Owing to the complexity of modern TPSs, it is not practicable to check every pathway in every program for corruption, nor is it likely that such a failure will occur. However, it is good to have a standard set of plans that exercises a range of the software. Previous publications (e.g. Ref. [72]) have given examples of such tests, and a subset of the tests outlined in Section 9 could also be used. It is recommended that each institution develop its own set, consistent with the techniques that it uses, based on the following broad principles.

(a) Look for reproducibility, not accuracy: the result of each test should be exactly the same as the original from the commissioning results. When software has been upgraded with new or improved algorithms, output from the new version becomes the benchmark.
(b) The test plans do not have to be good treatment plans: aim to test as much of the software as possible in a short time; for example, hard and dynamic wedges, blocks and MLCs, symmetric and asymmetric fields, with and without inhomogeneity corrections, etc., can be combined in a multibeam plan. Only if a variation is detected is there a need to isolate its cause.
(c) Be aware of different options: if more than one algorithm is invoked or explicitly chosen under different conditions, test all that are used.
(d) Be sure to repeat the test plans from scratch, including the image transfer if possible, so that the entire process is checked, not just the dose calculation.

One example could be:

(1) CT slices through the thorax, inhomogeneity correction algorithm turned on.
(2) Anterior: low energy, 15 cm wide, symmetric, unwedged, unblocked.
(3) Right lateral: low energy, asymmetric (2 cm, 8 cm), 60° hard wedge, MLC.
(4) Posterior: high energy, 8 cm wide, symmetric, two shielding blocks.
(5) Left lateral: high energy, asymmetric (0 cm, 10 cm), 30° dynamic wedge, unblocked.

Similarly, another plan could be developed for electrons if these are used in the department, with and without bolus at low and high energy.

10.2.9. QC test 9: Monitor units/time

Purpose: To check that there has been no change to the MU/time calculation of the TPS.

Procedure: For the test plans from QC test 8, use the TPS to calculate the MUs/time and check for exact agreement with previous data.

10.2.10. QC test 10: Plan details

Purpose: To check that the plan information shown on the hard copy has not changed.

Procedure: For the test plans from QC test 8, check that the isocentre co-ordinates, details of field size, SSD, wedges, blocking, etc., are printed out exactly as before.

10.2.11. QC test 11: Electronic plan transfer

Purpose: To check that there has been no change to transfer protocols and data.

Procedure: A standard set of test cases that exercises the most commonly used parts of the transfer process should be maintained. Again, this could be the output from plans from QC test 8 or a subset of test cases from Section 9.7.2. This set of test transfers should be run whenever data files, code, system software or other parts of the TPS and/or machine control systems are modified or updated. As part of commissioning, pick a subset of test cases from Section 9.7.2 for the periodic testing of the transfer.

10.2.12. QC test 12: Brachytherapy revalidation

Purpose: To check that there has been no change to brachytherapy dose distributions and time calculations.

Procedure: Depending on the isotopes and techniques used, repeat brachytherapy tests 2, 6, 7 and/or 8 from Section 9.5.2 to check that the brachytherapy dose distributions agree with the commissioning results and that treatment times are consistent with current activities and air kerma rates.

10.2.13. QC test 13: Plan details

Purpose: To check that the plan information shown on hard copy has not changed.

Procedure: For the test plans from QC test 12, check that source co-ordinates, dose rates, dwell times, etc., are printed out exactly as before.

10.2.14. QC test 14: Independent dose and time check

Purpose: To check that the TPS continues to calculate the dose and time correctly.

Procedure: Depending on the isotopes used, repeat one or more of brachytherapy tests 3, 4 or 5 from Section 9.5.2 to check, in particular, that isotope activities and air kerma rates are still handled correctly.

10.2.15. QC test 15: Electronic plan transfer

Purpose: To check that there has been no change to transfer protocols and data.

Procedure: A standard set of test transfers should be run periodically and whenever data files, code, system software or other parts of the TPS and brachytherapy unit control systems are modified or updated. A subset of the cases tested during commissioning (see Section 9.7.2) should be used for the testing of the transfer.

10.3. RECOMMISSIONING AFTER UPGRADES

10.3.1. Hardware

One should be aware of the likely impact of hardware upgrades on TPS performance. Specific tests for a changeover or a new component can often be performed. Use any automated TPS calculation check that is available. Calculation of standard plans (e.g. QC test 8) is reasonable but should not be taken as an assurance that there are no problems. A hardware change is more likely to create a problem indirectly than directly; for example, addition of a new hard disk may affect beam or plan data if directory pathways and links are not redefined correctly. This is especially important with multiple workstations: check that all are accessing and storing data correctly.

10.3.2. Operating system software and configuration

Operating system upgrades or reconfigurations are just as important as changes of the hardware. The operating system version should not be changed without specific approval of the vendor, a certification of compliance for the software and a notification of change for the users. Even minor system upgrades or patches may potentially affect the performance of the TPS. Do not add third party software without the vendor's approval, and perform a full system backup before installing it.

10.3.3. Treatment unit data: Recommissioning or additional data

If a new machine is installed or machine data are measured in conjunction with a new feature (e.g. an MLC) or as part of an ongoing QA programme, it may be necessary to change or update the TPS data. Such a changeover needs to be handled carefully. The ideal is to set up an alternative directory for testing

purposes only, or to decommission one workstation until the new data are ready and then introduce the new data. Always make sure that the original data are backed up and can be retrieved before changing the data. Planning systems differ in their sensitivity to changed machine data. Some invalidate previously stored treatment plans when recalled, others issue a warning and some take no action. Even if changes are minor, make sure that the changeover date is documented and that users are aware of the changes.

10.3.4. Treatment planning system software updates and upgrades

It is best to evaluate and test new software independently of the current version if this can be achieved. Back up the software and ensure that it can be retrieved. If the installation procedures require an immediate overwrite, there will be little time for detailed testing and clinical plans will need to be scrutinized more carefully than usual. Vendors usually provide release notes indicating changes or enhancements in the software. If they do not provide these, request such information. Those changes that might affect dose calculations should be noted and investigated. If an algorithm is added or altered, differences from previous versions for a substantial set of field sizes, shapes, modifiers and obliquities should be determined and documented. Typically software updates will fix known problems and introduce minor changes; some upgrades will also introduce new functionality. New features should be tested to ensure that they work as stated. If the new feature (e.g. a stereotactic radiation therapy option) involves a new dose calculation component, it should go through a full, detailed commissioning process. Bug fixes should also be tested. Also test to see if local problems not reported to or acknowledged by the vendor still persist, since problems often disappear as a product matures, although the converse is sometimes true, and a feature seldom used by others but important to you may no longer be available.

The hospital's documentation should be updated as appropriate to reflect the new software version.

It is not sufficient to check those elements known to have changed. A standard set of plans should be checked, as detailed in QC test 8. Compare plans performed with the new version with the same plans performed with the old version. Perform some simple (single beam) checks, comparing isodose lines and/or specific points.

Follow with comparisons of complex plans that exercise all features. If no algorithm changes are expected, confirm that the calculation results are identical to those of the same calculation before the change. If the algorithm has been changed and differences are observed, verify that the differences are consistent with the change.

Some testing should check the entire system, from data entry to hard copy output (including MU or time calculations, if used). It is often tricky to change from one version to the next unless a specific plan for upgrades is used, so it is important to create a transition plan and then follow it through.

11. PATIENT SPECIFIC QUALITY ASSURANCE

11.1. INTRODUCTION

The procedures outlined in the previous section give an assurance that the TPS and associated operations and data transfers are functioning correctly over time. However, as described in Section 6, this is only one aspect of treatment planning QA. Another very important component is the series of checks undertaken to ensure that each individual patient's treatment plan conforms to the established protocols and is delivered as planned.

Figure 16 summarizes the key stages of the treatment planning process. Highlighted boxes indicate points at which redundancy checks should be undertaken. The method, time sequencing and personnel involved may vary from institution to institution, but it is of vital importance that these checks be integrated into the overall process.

For each check, the person conducting the check should document that the check was completed by initialling or signing an appropriate form or chart.

11.2. CONSISTENCY DURING PLANNING

The checks undertaken as the plan evolves are somewhat different in that they may be undertaken by the person generating the plan rather than by a second person. These are common sense checks for, for example, reasonableness of the images and structures, the beam geometry (SSDs, wedges, field sizes, etc.), that the isocentre location makes sense and that the plan is consistent with other plans for the same anatomical site and with the radiation oncologist's requirements. Staff need to develop an analytical approach to planning and to question anything different from the norm.

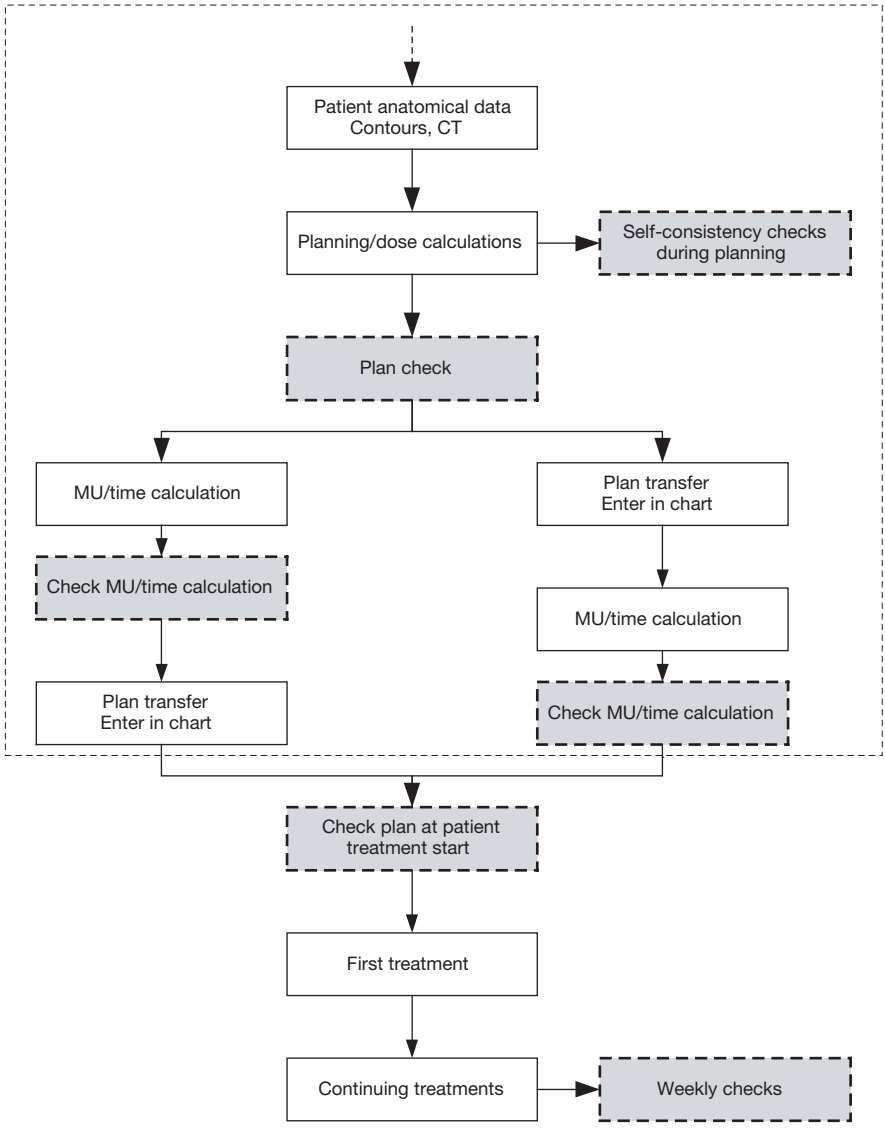

FIG. 16. Outline of treatment planning and delivery QA.

11.3. PLAN CHECK

Every treatment plan must be closely checked by a person different from the original treatment planner. This independent check should be performed by a radiation oncology physicist. In some cases, this check may be performed by a senior treatment planner, but in all cases should be done by someone with experience both of treatment planning and of the output from the TPS. It is useful to work through a checklist for each plan. The items to be checked will depend upon local equipment and practices and upon the particular treatment plan. The list below is an example, and is not necessarily exhaustive. Usually the checking entails examination of hard copy output of the treatment plan, although it is possible and sometimes necessary to check some of the plan details using the TPS console.

Checklist for a treatment plan:

(a) Have the image and contour data been input correctly? (Orientation and extent of slices: only for 3-D.)
(b) Do the outlines of the target volume and other structures seem reasonable?
(c) Is the plan consistent with the radiation oncologist's dose prescription?
(d) Does the plan look reasonable? Is it consistent with other plans for that body site?
(e) What is the relationship between the isocentre and the external anatomy (reference marks)?
(f) Is the beam geometry appropriate and achievable on the linear accelerator or ^{60}Co machine?
(g) Are asymmetric collimators used? (If not routine, this may require highlighting.)
(h) Have the beams been weighted appropriately?
(i) Do the beams cover the target volume adequately? (Is the dose variation throughout the target acceptable?)
(j) Is the plan normalization point and/or value correct?
(k) Have the dose constraints been satisfied? (DVHs and/or maximum doses to structures.)
(l) Is tertiary blocking used? If there is an automated transfer to a block cutting machine, have the correct blocks been transferred? Is the orientation of the blocks clearly specified (e.g. on a plot of the BEV)?
(m) As above, for MLCs (including dynamic) and compensating filters.
(n) Have wedges been used? If so, are they appropriate and orientated correctly?
(o) Have all the appropriate hard copies been printed out and collated?

(p) Have treatment parameters been transferred to the department's record and verify system? (If applicable: this may be an automated or manual process.)
(q) The maximum dose for the plan should be determined and evaluated.

The majority of treatment plans usually fall into several broad categories, since standard techniques are used for different anatomical sites. For these, it is relatively easy to spot anything unusual. However, there will also be plans developed for specific cases. These should be checked more carefully, both for human error in creating the plan and also to ensure that extreme or previously untried beam geometries still produce sensible dose distributions. The plan and its special characteristics should be flagged by, for example, a footnote to the checklist, so that treatment staff in particular are prepared for the treatment.

11.4. MONITOR UNIT/TIME CHECK

If the TPS is used to calculate MUs or treatment times, all the factors that are printed out as part of the MU/time calculation information should be checked to see that they fall within the expected ranges. There should be some form of independent (redundant) check of the MUs/time calculated. This may be performed with an independent computer program or by a manual calculation. The second calculation can be a simple one, ignoring second order effects such as loss of scatter due to beam blocking and change in depth dose due to wedge hardening, none of which will make a large difference to the MUs/time. For a complex plan, or one with inhomogeneity corrections, it may be difficult to calculate independently all factors, but a secondary check will indicate whether the MUs/time are reasonable. The main goal of the secondary (check) MU/time calculation is to prevent a serious error in the calculated MUs or treatment time.

Some departments prefer to use an independent computer program (separate from the TPS) for the MU/time calculation. If so, it is important to check that any factors that have been obtained from the TPS have been correctly entered.

It may be possible to use the TPS's MU/time calculation as the redundancy check of the independent program. If the TPS does not provide an MU/time calculation, a primary and secondary calculation of the MUs/time should always be performed.

11.5. EXPORT AND HANDLING OF PATIENT SPECIFIC DATA: PRETREATMENT CHECKS

Output from the TPS may include any of the following:

(a) A hard copy of planar isodose distributions;
(b) A hard copy of beam parameters and MU/time calculations;
(c) A hard copy of BEVs, DRRs and customized ports (blocks and MLC shapes);
(d) Text files that are transferred electronically to a block cutting machine or an MLC.

It is important that naming conventions and storage policies for hard copy output and files be established and observed. Much of this will be governed by local practices, and the detail is beyond the scope of this report. However, by way of example, the policy should include the following:

(1) Should a hard copy be produced before or after the plan is approved; how is the final plan denoted?
(2) Beams, customized ports and MLC shapes should be labelled unambiguously so that there is no confusion about the patient to whom they belong, the orientation and the initial and boost fields.
(3) If files are transferred across a network, it should be understood who transfers them. The transfer should not be performed until the plan is finalized and approved. Although direct transfer to patient management systems is very efficient, it is also potentially dangerous if it leads to inadequate review of data before they are used to deliver a treatment. It is important to ensure that sufficient redundancy checks are in place.

Before the patient's first treatment, a check of all treatment parameters should be made by one of the treatment staff. If data have been imported to a patient management system that interfaces with the linear accelerator or ^{60}Co machine, then each beam should be called up in sequence and all parameters (collimator settings, gantry angle, MLC shape, MUs/time, etc.) should be cross-checked against the treatment plan. For dynamic treatments (moving collimators, leaves or gantries), the 'treatment' should be delivered first in the absence of the patient to ensure that there are no problems.

11.6. ONGOING CHECKS (WEEKLY)

Many treatment plans require changes to be implemented at various points throughout the course of the radiotherapy. Some examples are changes to beam arrangements (e.g. AP–PA switching to laterals), changes to cone down or boost volumes, moving junctions between adjacent fields, changes to bolus used for only part of a course, changes to the daily fraction size or fractionation schedule and changes to treatment breaks. The QA programme should include regular (weekly) checks of treatment progress to ensure that such changes are or have been implemented correctly and at the right time.

In addition, a weekly check ensures that unscheduled changes (e.g. a missed treatment due to a machine breakdown) are compensated for.

11.7. OTHER PATIENT SPECIFIC ISSUES

Other patient specific issues are:

(a) Plans involving bolus require careful scrutiny, because TPSs may handle the bolus in different ways. It may be linked to the beam or to the anatomy; it may be possible to switch its effect off or on for part of the course; doses may be normalized to the bolused or unbolused geometry.
(b) Non-standard CT protocols (e.g. patient prone, scanned feet first or zoomed in to image just one leg) create the possibility of mistreatment, even treating the wrong side of the patient. Such plans should be checked more carefully. An additional marker on the image may be used as a redundant check of orientation.
(c) Metal prostheses present a twofold problem [100–103] in that they may distort a CT image, so that delineation of the target volume is compromised, and in that the CT numbers that are used for pixel based inhomogeneity corrections will be unreliable, leading to errors in electron density. The TPS may not even support electron density values of that magnitude. Procedures adopted could include alternative beam arrangements, or some manual adjustment of the computed dose based on experiment, or notification to the radiation oncologist that the dose is subject to significant uncertainty compared with normal.
(d) It is important, particularly for out of the ordinary plans, to be aware of the limitations of the calculation algorithms and of the consequent uncertainty and/or error in the dose distribution. For TPSs for which more than one calculation algorithm has been commissioned and for which users may choose between algorithms depending on the

application, additional care is needed to ensure that an appropriate algorithm has been used.

11.8. UNUSUAL BEHAVIOUR

Unusual behaviour can often be a warning sign of a problem that has escaped detection by routine QA. It is of vital importance that all such events, even if they seem trivial, are documented and investigated. Failure to do so can lead to major (and continuing) errors of the type described in Section 1.4.

When using the TPS, unexpected events sometimes occur. A program may terminate without warning or a cryptic error message may appear on the screen. It is good practice to have a fault logbook or computer log system accessible at each workstation, to be used to document problems. The particular problem and the circumstances that led to it should be described in detail, including any error messages that were displayed. The TPS manager should review the fault logbook regularly, and investigate such issues thoroughly. Is the problem reproducible? Is it simply a nuisance or is there a chance that it could affect the treatment plan? If the problem cannot be explained satisfactorily after investigation, it should be reported to the vendor.

11.9. IN VITRO AND IN VIVO DOSIMETRY AND IMAGING

There is a place for validation of treatment plans with appropriate dosimetry measurements, if used with discernment and caution. In vitro dosimetry with an anthropomorphic phantom loaded with thermoluminescent dosimeters or other small volume detectors is useful for validating new software or new treatment techniques. It is better to use this approach for categories of plans rather than for patient specific problems. A hastily conducted experiment to reproduce an unusual plan is likely to be ambiguous, leading to questions including ‘Is the plan in error?’ or ‘Were the measurements inaccurate?’.

In vivo dosimetry can be useful, but it is important to recognize that the measurement may have large uncertainties. The results of thermoluminescent dosimeters or diodes on the patient surface to estimate the dose at depth, measurement at field junctions and edges that are subject to daily patient set-up variation, or simply the statistical uncertainty associated with a single thermoluminescent dosimeter or diode reading, necessitate careful interpretation. It is better to use an in vivo measurement as a redundancy check of the delivery of a plan than as a means of determining the plan’s accuracy (i.e. it is

not good practice to accept a plan subject to the results of an in vivo measurement or until a tolerance dose, as determined by measurement, is reached). A number of institutions include an in vivo measurement at the beginning of a treatment as part of their initial treatment QA checks. This can be good practice when the thermoluminescent dosimeters or diodes are located near the centre of the field and away from rapid dose gradients.

Portal films and electronic portal imaging confirm that the planned beams are correctly shaped and directed. Whether or not a simulator film is also available, comparison of a portal image with a DRR is a very useful check, as geometrical errors in field shape or placement can lead to very large differences between the desired dose distribution and the delivered dose distribution.

12. SUMMARY

The commissioning and QA of computerized radiation treatment planning is complex. The length of this report represents a compromise between the need for a comprehensive report to deal with the complexity and a desire for simplicity. As indicated in Section 2.1 and Fig. 1, treatment planning is the hub of the radiation therapy process, and in itself consists of multiple steps. Treatment planning involves many sources of information, including patient images, possibly from various imaging modalities, outlines of target and critical volumes as determined by a physician, radiation data such that accurate dose distributions can be calculated and accurate descriptions of the radiation machines or the radioactive isotopes that will be used for the treatment. It is the coming together of multiple sources of information in the TPS that makes the commissioning and QA procedures complex. This is in contrast to the commissioning and QA of simulators and megavoltage therapy machines, for which such procedures have existed for many years. Furthermore, TPSs from different vendors vary dramatically in functionality as well as in the capabilities and limitations of the specific algorithms that are used.

In view of the complexities described above, this report does not provide a simple protocol that can be followed step by step for the commissioning and QA of specific TPSs. Instead, this report provides guidance to the TPS user on the types of test and procedure that should be considered. Specific examples of tests and procedures are given; however, the user may have to modify these depending on his or her TPS, on the irradiation facilities available or on the specific treatment techniques that will be employed.

There is a general and dangerous tendency to use computerized outputs without an appropriate level of scepticism concerning their overall accuracy. Users of TPSs need to have enough basic understanding that they can examine plans at a global level in order to decide if the plan produced and the number of MUs calculated makes common sense and is reasonable. Section 1.4 summarizes various errors specifically related to treatment planning that have been reported publicly. As indicated, the major issues related to these errors are summarized by four key words:

(a) Education;
(b) Verification;
(c) Documentation;
(d) Communication.

These key words also summarize the goals, objectives and outcomes of a well structured QA programme in radiation treatment planning. Thus the major rationale for the multiple commissioning tests described in Section 9 of this report relates to education, verification and documentation. Communication is something that is dependent on the will and skill of the staff involved in the treatment planning process and needs to be encouraged at all levels, from upper management and down, as well as from the front line employees and up.

Computers continue to become faster and more refined, allowing treatment planning algorithms also to become more sophisticated and therefore more accurate. The present trend is towards treating more patients with IMRT using inverse treatment planning. While this report touches on some issues related to IMRT and inverse planning, as experience evolves more detailed information and procedures will need to be developed for their commissioning and QA. Indeed, this statement can be generalized for the evolution of any technology related to the radiation treatment process.

In this summary, some broad recommendations are highlighted:

(1) Adequate resources (staff, computers and radiation measurement equipment) must be available to implement a successful commissioning and QA programme.
(2) Staff should have the appropriate basic qualifications to participate in the treatment planning process (i.e. physicians, medical physicists, dosimetrists and radiation therapists (radiographers and radiation therapy technologists) should have the appropriate professional training and certifications).

(3) One medical physicist should be given the responsibility for the commissioning of the TPS and for implementing a QA programme to ensure its ongoing validity.
(4) While the responsible medical physicist should make use of this report as a guide for commissioning and QA, it should be emphasized that this report is not prescriptive of everything that needs to be done. Thus this report can be used as a guide, but modifications may have to be made depending on the local circumstances (e.g. the type of radiation treatment devices available, the types of technique used in the department, the type of TPS available and the types of imaging technology used).
(5) Commissioning tests such as those described in Section 9 are required to ensure accurate calculation procedures. In addition, tests such as these are a tremendous aid for educating the user on the functionality, capabilities and limitations of the TPS. Test cases developed during commissioning can be used for ongoing QA.
(6) QA procedures such as those described in Section 10 are essential to ensure that the databases and the software and the hardware have not changed since the commissioning or recommissioning of the system.
(7) Some recommissioning tests will have to be performed whenever new versions of any software are installed.
(8) A data logbook should be maintained describing the faults and error messages that have occurred as well as any specific calculation anomalies. Significant errors, or the possibility of occurrence of such errors, that are clearly related to the software and not to the user should be reported to the vendor immediately.
(9) Documented, patient specific QA procedures should be developed for each institution. These procedures should include an independent quality check of the resultant dose distribution and an independent check of the MU/time calculation for each beam.
(10) In-house training should be provided to all the treatment planning staff. Periodic refresher training should also be provided to ensure that no errors or inconsistencies have evolved in the routine clinical treatment planning process.

The modern technology of radiation oncology continues to evolve at a rapid rate. Monte Carlo techniques for treatment planning are becoming available for clinical use [104–107]. Inverse treatment planning is a requirement for IMRT [53]. The development of helical tomotherapy and how this can be combined with on-line CT imaging for patient repositioning and adaptive radiation treatment is another manifestation of the change in technology [84]. The use of biological modelling for treatment plan evaluation

is rapidly approaching clinical utility [49–52, 108], although at the present time it should still be used with extreme caution. Controlled breathing or gated treatment is being implemented as a means of minimizing organ motion during treatment [109–112]. It is clear that with each of these improvements and advancements, unique issues do arise in the context of radiation therapy planning, commissioning and QA. It is a result of both the complexity of the treatment planning process and the rate of change of new technologies that this report cannot be prescriptive but can only be an aid to describing the types of issue that the radiation oncology physicist should consider in the development of a commissioning and QA programme. We expect that with careful consideration of the general procedures described in this report, the treatment error rate will be minimal and the benefit to the patient will be maximized. After all, the ultimate goal of the radiation treatment process is to deliver a high dose of radiation to the patient's tumour using both safe and properly optimized procedures, so that the quality of life of the cancer patient will be maximized.

Appendix

TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

The tests detailed in Tables 62–68 should be carried out after careful system set-up and machine–source configuration, as described in Section 9.2. Not all the tests need to be performed, depending on the techniques and protocols used. The rationale for all these tests is not only to check the validity and accuracy of the results but also to get used to the TPS and understand its capabilities and limitations before clinical use.

TABLE 62. GENERAL TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

		Basic	Full	Special issues
Section 9.3. Patient data		2-D, no CT	CT 2-D or 3-D	Other modalities
	Patient data acquisition	1	1	
	Patient data input	2	2	2
	Anatomy	7	13	1
	Subtotal	10	16	3
Section 9.4. External beams		2-D, simple blocks, no heterogeneity	3-D, MLC, heterogeneity, non-coplanar	Special techniques
	Machine–beam set-up	10	15	4
	Dose (photon)	5	10	3
	Dose (electrons)	4	7	
	Dose (operational)	3	1	
	Dose (MU)	5	3	2
	Subtotal	27	36	9

TABLE 62. GENERAL TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

		Basic	Full	Special issues
Section 9.5. Brachytherapy (sources)		All techniques and sources	Special techniques or sources	Operational
	Brachytherapy (dose)	4	4	2
	Brachytherapy (geometry)	2	2	
	Subtotal	6	6	2
Section 9.6. Evaluation		2-D planning	3-D CRT	
	Dose display	5		
	DVHs		10	
	Biological effects		3	
	Subtotal	5	13	
Section 9.7. Output and data transfer (manual or electronic)		Simple coplanar techniques	Non-coplanar conformal fields	Safety management
	Output	1		
	Plan transfer	9	5	1
	Subtotal	10	5	1
Section 9.8. Clinical tests		Simple non-conformal	Conformal or special techniques	
	Clinical	6	5	
	Total	63	81	15

TABLE 63. PATIENT DATA TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (2-D planning, no CT)	Full tests (CT and/or 3-D CRT)	Special issues
Section 9.3.1. Acquisition of patient information			
Acquisition test 1	Manual patient contour acquisition		
Acquisition test 2		CT data acquisition	
Section 9.3.2. Entry or transfer of input anatomical data			
Input test 1	Digitizer calibration		
Input test 2	Manual contour entry		
Input test 3		CT data and orientation	
Input test 4		CT tools in TPS	
Input issue 1			Other imaging modalities
Input issue 2			Patient database
Section 9.3.3. Anatomical model			
Anatomy test 1	Representation of contours		
Anatomy test 2		Manual contouring from CT	
Anatomy test 3		Automatic contouring	
Anatomy test 4	Editing of contours		
Anatomy test 5		Generating 3-D object description	

TABLE 63. PATIENT DATA TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no CT)	Full tests (CT and/or 3-D CRT)	Special issues
Anatomy test 6		Generating new contours	
Anatomy test 7		Object expansion	
Anatomy test 8	Creating densities for manual contours		
Anatomy test 9		Creating densities from CT	
Anatomy test 10		Creating anatomical bolus	
Anatomy test 11		Editing of CT densities	
Anatomy test 12	Defining points, lines, marks		
Anatomy test 13		2-D image display	
Anatomy test 14		2-D image display tools	
Anatomy test 15		Generating 2-D reconstructed images	
Anatomy test 16		3-D display and associated tools	
Anatomy test 17	Tools for the manipulation of anatomical data		
Anatomy test 18	Measurement tools (geometry)		
Anatomy test 19	Basic co-ordinate system		
Anatomy test 20		3-D co-ordinate readout	
Anatomy issue 1			Use of multiple image data sets

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
Section 9.4.2. Machine capabilities and beams			
Beam test 1	Machine description and capabilities		
Beam test 2	Machine readout conventions and scales		
Beam test 3	Machine parameter limitations		
Beam test 4	Collimator jaw setting		
Beam test 5		Asymmetric jaws	
Beam test 6	Blocks (and trays)		
Beam test 7		MLC shape	
Beam test 8		Automated field shaping	
Beam test 9	Beam set-up (SSD or SAD)		
Beam test 10	Beam location (x, y, z)		
Beam test 11	Gantry and collimator		
Beam test 12		Arcs	
Beam test 13	Wedges		

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
Beam test 14		Compensators	
Beam test 15		Electron applicators	
Beam test 16		Bolus	
Beam test 17	Axial planes		
Beam test 18		Non-axial planes	
Beam test 19		3-D displays	
Beam test 20		BEV display of beam and anatomy	
Beam test 21		DRR calculation and display	
Beam test 22		Display of portal images	
Beam test 23	Multiple beam isocentre functions		
Beam test 24		Field matching	
Beam test 25		Missing tissue and dose compensation	
Beam issue 1			Inverse planned IMRT
Beam issue 2			Radiosurgery

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
Beam issue 3			Large field techniques
Beam issue 4			Complex table motions
Section 9.4.3. Photon beams			
Photon test 1	Field shaping (square and rectangular)		
Photon test 2		Asymmetric fields	
Photon test 3	Shaped fields		
Photon test 4	Beam directions (fixed fields)		
Photon test 5	Arc rotations		
Photon test 6	SSD dependence		
Photon test 7	Mechanical (hard) wedges		
Photon test 8		Automatic wedge	
Photon test 9		Dynamic wedge	
Photon test 10	Oblique incidence		
Photon test 11	Missing scatter		
Photon test 12	Buildup region behaviour		
Photon test 13	Density corrections		

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
Photon test 14		Missing tissue and dose compensation	
Photon test 15		Forward planned IMRT	
Photon issue 1			Inverse planned IMRT
Photon issue 2			Radiosurgery
Photon issue 3			Large field techniques (TBI, HBI, etc.)
Section 9.4.4. Electron beams			
Electron test 1	Field shaping (square and rectangular)		
Electron test 2	Shaped apertures		
Electron test 3	Shielding and skin collimation		
Electron test 4	SSD dependence		
Electron test 5	Slab bolus		
Electron test 6		Shaped bolus	
Electron test 7	Oblique incidence		
Electron test 8		Complex surface shapes	

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
Electron test 9	Bulk inhomogeneity corrections		
Electron test 10		CT based inhomogeneity corrections	
Electron test 11		Arcs	
Section 9.4.5. Operational issues			
Operational test 1	Algorithm choice		
Operational test 2		Inhomogeneity corrections	
Operational test 3	Calculation validity		
Operational test 4	Calculation grid and window		
Section 9.4.6. Absolute and relative dose			
MU test 1	Basic MU calculation for open fields		
MU test 2		MU calculation for tangential fields	
MU test 3	MU calculation for wedged fields		

TABLE 64. EXTERNAL BEAM RADIOTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning, no MLC, symmetric jaws, no inhomogeneity)	Full tests (3-D, MLC, non-coplanar)	Special issues (special techniques)
MU test 4 and 4a	MU calculation for blocked fields		
MU test 5 and 5a		MU calculation for MLC shaped fields	
MU test 6		MU calculation with inhomogeneities	
MU test 7		Off-axis point calculations	
MU test 8	Dose prescription		
MU test 9	Dose distribution units		
MU issue 1			Documentation for treatment chart
MU issue 2			Clinical check procedure

TABLE 65. BRACHYTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (all techniques and radionuclides)	Full tests (special techniques or sources)	Special issues (operational)
Section 9.5.3. Dose calculation			
Brachytherapy dose test 1	Parameterization and reference data		
Brachytherapy dose test 2	Dose distribution for a single source		
Brachytherapy dose test 3		Dose rate for a variable length	
Brachytherapy dose test 4	Correction for decay at the starting time		
Brachytherapy dose test 5	Computation of the treatment time		
Brachytherapy dose test 6		Correction for decay during application	
Brachytherapy dose test 7		Dose integration for a permanent implant	
Brachytherapy dose test 8		Dose distribution for a stepping source	
Brachytherapy dose issue 1			Source arrangement and applicators

TABLE 65. BRACHYTHERAPY TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (all techniques and radionuclides)	Full tests (special techniques or sources)	Special issues (operational)
Brachytherapy dose issue 2			Results update after changes
9.5.3. Geometry			
Brachytherapy geometry test 1	Quality of geometrical reconstruction		
Brachytherapy geometry test 2	Manual identification of sources		
Brachytherapy geometry test 3		Automatic identification of sources	
Brachytherapy geometry test 4		Total versus active length	

TABLE 66. PLAN EVALUATION TOOLS TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (2-D planning)	Full tests (3-D conformal planning)	Special issues
Section 9.6.1. Dose display			
Dose display test 1	Plan normalization		
Dose display test 2	Isodose lines and surfaces		
Dose display test 3	Cold and hot spots		
Dose display test 4	Point dose display		
Section 9.6.2. Dose–volume histograms			
DVH test 1		Types of DVH	
DVH test 2		Plan normalization	
DVH test 3		Relative and absolute dose comparisons	
DVH test 4		Relative and absolute volume	
DVH test 5		Histogram dose bin size	
DVH test 6		Compound structures	
DVH test 7		Consistency with dose display	
DVH test 8		Calculation point sampling	
DVH test 9		Comparison guidelines	
DVH test 10		Dose and volume statistics	

TABLE 66. PLAN EVALUATION TOOLS TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (2-D planning)	Full tests (3-D conformal planning)	Special issues
Section 9.6.3. Biological effects			
Bioeffect 1		NTCP	
Bioeffect 2		TCP	
Bioeffect 3		Fractionation and other	

TABLE 67. PLAN OUTPUT TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (simple coplanar techniques)	Full tests (non-coplanar conformal fields)	Special issues (safety management)
Section 9.7.1. Plan output			
Plan output check	Hard copy visual check		
Section 9.7.2. Plan transfer (manual or electronic)			
Transfer test 1	TPS scale convention		
Transfer test 2	Scale conventions for TPS and equipment		
Transfer test 3	Angle readings		
Transfer test 4		Table co-ordinates	
Transfer test 5	Jaws		
Transfer test 6	Machine definition		
Transfer test 7		Machine motions	
Transfer test 8	Wedges		
Transfer test 9		Blocks	
Transfer test 10		MLC	
Transfer test 11	Electron applicators		

TABLE 67. PLAN OUTPUT TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING (cont.)

	Basic tests (simple coplanar techniques)	Full tests (non-coplanar conformal fields)	Special issues (safety management)
Transfer test 12	Uniqueness		
Transfer test 13		Miscellaneous devices	
Transfer test 14	Dose prescription		
Transfer issue 1			Additional safety requirements

TABLE 68. CLINICAL TESTS TO BE PERFORMED FOR TREATMENT PLANNING SYSTEM COMMISSIONING

	Basic tests (simple non-conformal techniques)	Full tests (conformal or special techniques)	Special issues
Clinical test 1	Open four field box		
Clinical test 2	Four field box with blocks		
Clinical test 3	Wedge pair		
Clinical test 4	CT plan		
Clinical test 5		Six field coplanar conformal prostate plan	
Clinical test 6		Conformal non-coplanar brain plan	
Clinical test 7		Combined photon–electron plan	
Clinical test 8	Brachytherapy gynaecological application		
Clinical test 9	Brachytherapy two plane breast implant		
Clinical test 10		Brachytherapy prostate ^{125}I plan	
Clinical test 11		Brachytherapy HDR or PDR test case	

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Annex

PUBLISHED BENCHMARK DATA FOR ASSESSING DIFFERENT SCATTERING CONDITIONS

Figures A–1 to A–3 are from Ref. [A–1], which presents a methodology based on the use of the quality index (QI) of photon beams (defined as the ratio of tissue phantom ratios for a 10 cm × 10 cm field and depths of 20 and 10 cm, respectively) for checking any kind of in-phantom perturbation in the dose distribution as compared with a water phantom reference situation. As an example and as a useful test, it is applied here to the dose perturbation resulting from the addition to a parallelepiped water-like phantom of one or two lateral columns of scattering material.

Figure A–1 represents the geometry that has been used both for the reference situation (Fig. A–1(a)) and for the situations where the scattering material is present either on one side (Fig. A–1(b)) or on both sides (Fig. A–1(c)). The measurements were carried out with a cylindrical 0.6 cm^3 Farmer type chamber, and a correction factor (CF) was obtained from the ratio of the readings with and without scattering material.

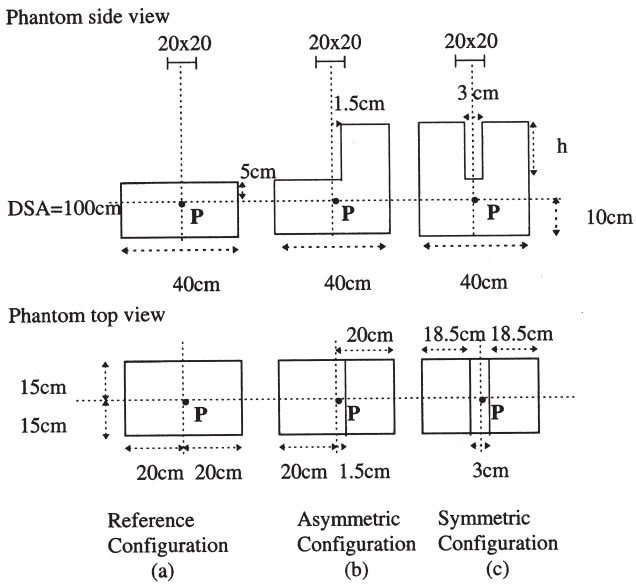

FIG. A–1. Experimental configurations designed to investigate the modification of the dose at the point of measurement (point P) when there are changes in phantom lateral scatter. Reproduced, with permission, from Ref. [A–1].

Figure A–2 represents the variation of CF as a function of the height *h* of one (Fig. A–2(a)) or both (Fig. A–2(b)) of the two columns. The CF as a function of QI is plotted in Fig. A–3 for four different values of *h* of the scattering columns. The equation of the linear fit is also given. The practical use of such data consists of computing the number of MUs to be set in order to give a well defined dose at point P for situations of Figs A–1(a), (b) and (c). The change in the MUs is the inverse of the change of the CF. Once the CF has been computed for a given beam quality QI_{user} and for one or several values of *h*, one can use Figs A–3(a) and (b) in a graphical way or with the linear fitting equation to estimate the expected value of the CF for the quality QI_{user}. To minimize the uncertainty in the computation of the CF, the dose set at point P must be large enough to obtain an integer number of MUs typically larger than 400. In addition to this test, it might be useful to compute the TPS's QI to make sure that it is consistent to within 2% of the experimental value for the same beam.

Figures A–4 to A–7 are from Ref. [A–2], which provides benchmark measured data, for 4 MV and 15 MV photons, for the four geometries shown in Fig. A–4. Figures A–5 and A–6 provide data for the layer geometry of Fig. A–4. Figure A–5 gives data for three field sizes, for a slab of density 0.31 g/cm^3, while Fig. A–6 gives data for slabs of three different densities for a 5 cm × 5 cm field size. For both these figures, the dashed curves represent the calculated correction factor (CFp), based on simple exponential attenuation of the primary component of the dose alone (i.e. neglecting scatter). These data illustrate how poor an approximation this is. Figure A–7 provides data for the mediastinum geometry of Fig. A–4, and shows the effect of scatter when the primary beam does not pass through an inhomogeneity. For data for the other geometries, refer to Ref. [A–2].

In contrast to Ref. [A–1], the data of Ref. [A–2] cannot be used directly, since it is very unlikely that the beam qualities at the 4 MV and 15 MV used for the measurements will match the beam quality of the TPS user. They are, however, useful to give an estimation of the order of magnitude of the perturbations expected in the presence of inhomogeneities for similar energies.

Figures A–8 and A–11 and Table A–1 are from Ref. [A–3]. The data in Table A–1 and Figs A–10 and A–11 correspond to film measurements for the geometries shown in Figs A–8 and A–9. The curves show the penumbral broadening due to electronic disequilibrium at the edge of a beam when it passes through a low density medium simulating lung. The profiles with and without inhomogeneity are renormalized to the beam axis. Therefore, the perturbations of the absolute dose (or number of MUs) must be assessed separately. More data are contained in Ref. [A–3].

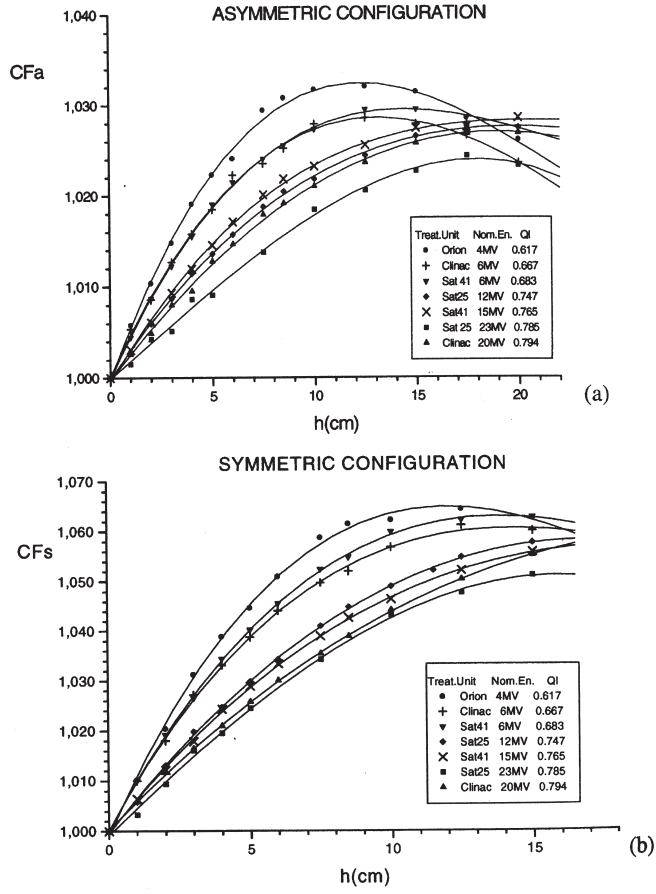

FIG. A–2. Asymmetric (a) and symmetric (b) correction factors as a function of height h of phantom lateral columns. Each curve is characterized by the treatment unit for which measurements have been performed, its nominal energy and photon beam quality index. Reproduced, with permission, from Ref. [A–1].

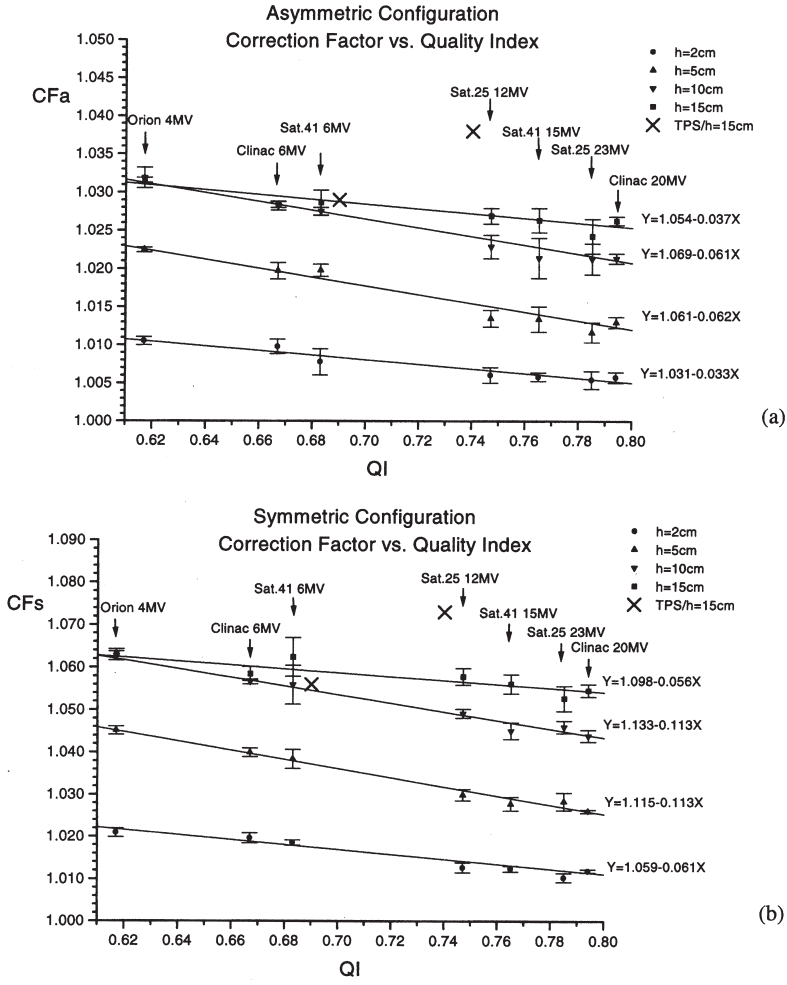

FIG. A–3. Correction factors as a function of quality index for (a) the asymmetric and (b) the symmetric configuration. For each height h, correction factors are calculated as the arithmetic mean between values obtained from two independent measurements. Errors are calculated as the quadratic sum of experimental and reproducibility errors. In order to use these results for TPS dose verification in conditions other than those of the standard case (h = 15 cm), a linear fitting was performed. The correction factor can then be obtained from curve interpolation. The cross corresponds to a typical TPS calculation for a 10 MV energy beam. Reproduced, with permission, from Ref. [A–1].

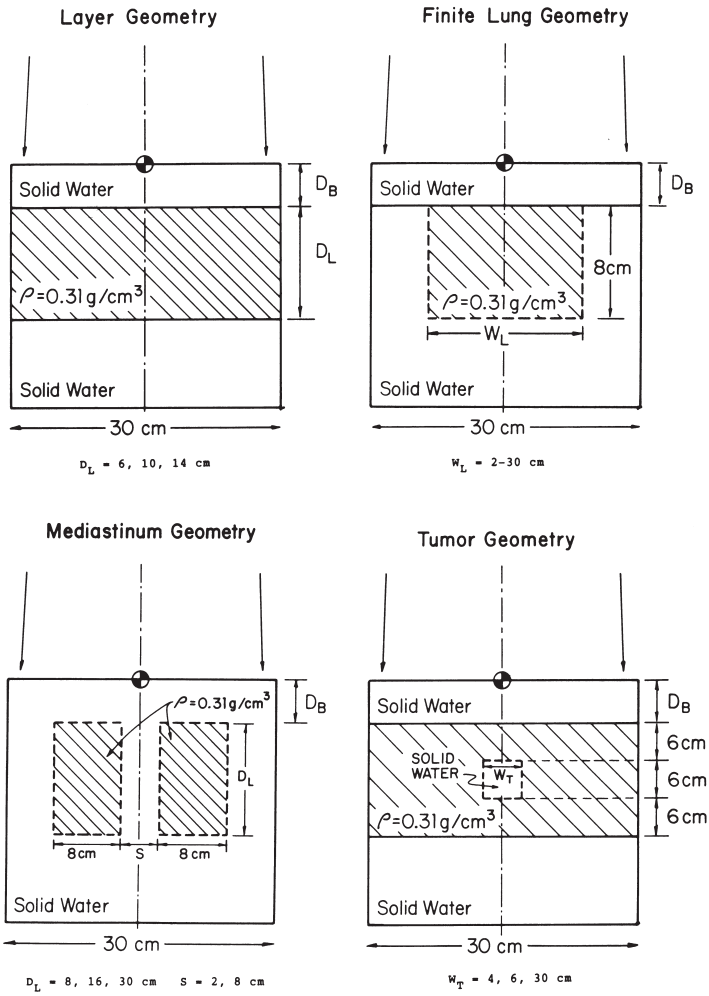

FIG. A–4. Schematic view of the four geometries studied. D_B is the thickness of the buildup layer of solid water, D_L is the thickness of the low density layer, W_L is the width of the lung volume, S is the separation between the lungs, W_T is the width of the tumour volume. Reproduced, with permission, from Ref. [A–2].

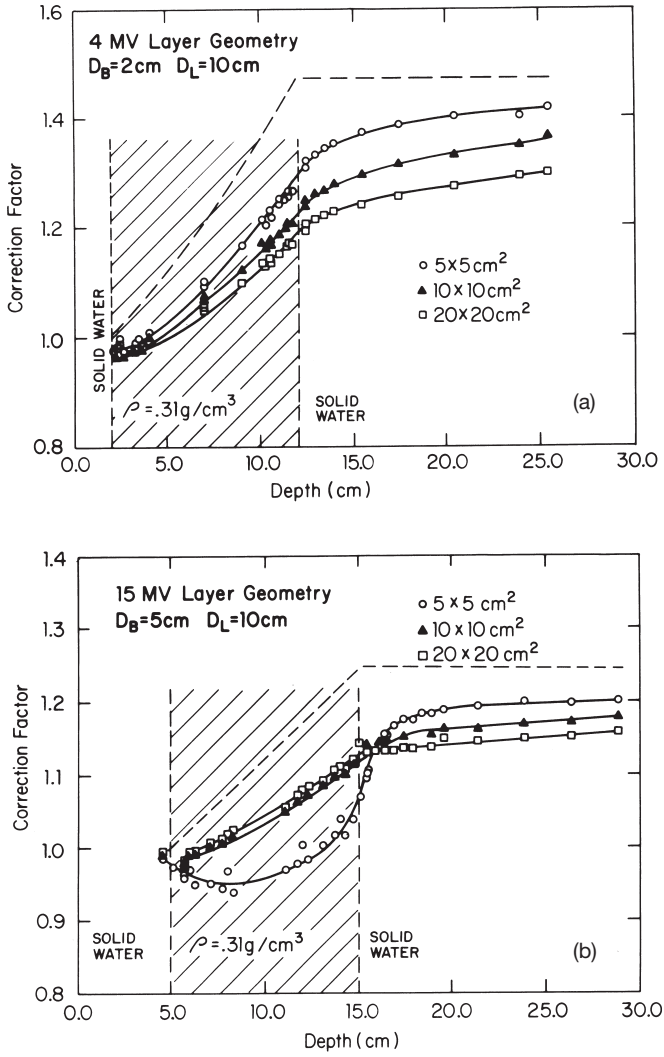

FIG. A–5. Correction factor for three different field sizes as a function of depth below the surface of the phantom. (a) 4 MV X rays, (b) 15 MV X rays. Reproduced, with permission, from Ref. [A–2].

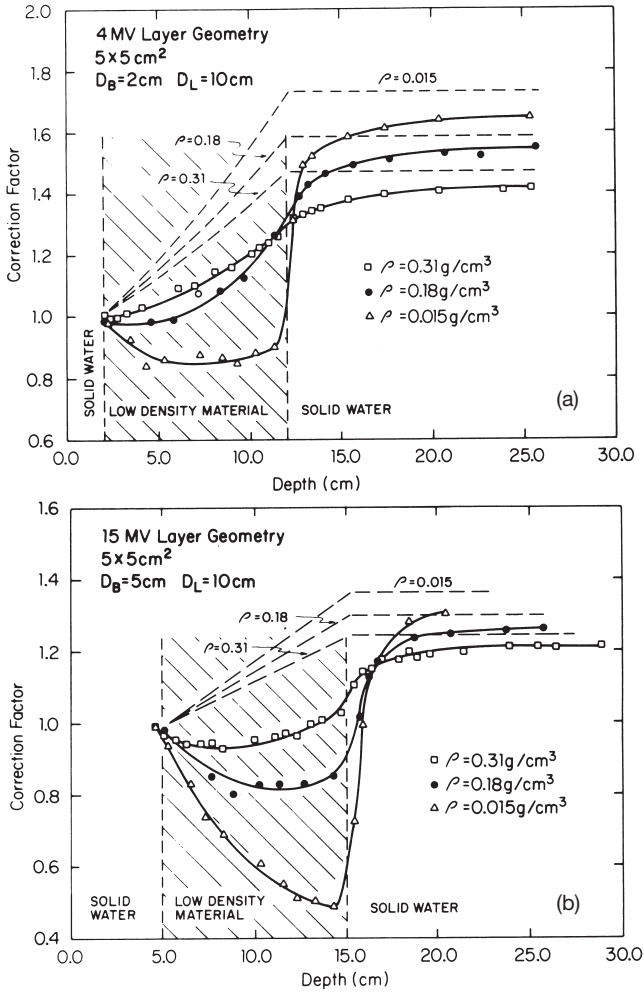

FIG. A–6. Correction factor for a 5 cm × 5 cm field as a function of depth below the surface of the phantom for lung densities of 0.015, 0.18 and 0.31 g/cm^3. (a) 4 MV X rays, (b) 15 MV X rays. Reproduced, with permission, from Ref. [A–2].

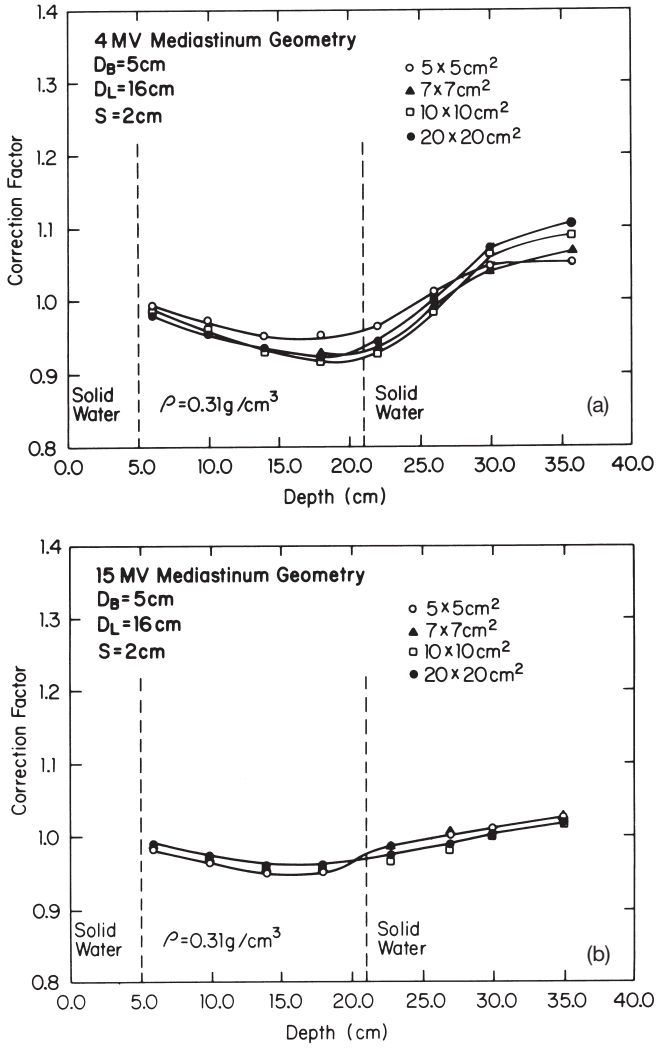

FIG. A–7. Correction factor as a function of depth below the surface of the phantom, measured along the central axis of the beam between two lungs with a separation of 2 cm, for different field sizes. (a) 4 MV X rays, (b) 15 MV X rays. Reproduced, with permission, from Ref. [A–2].

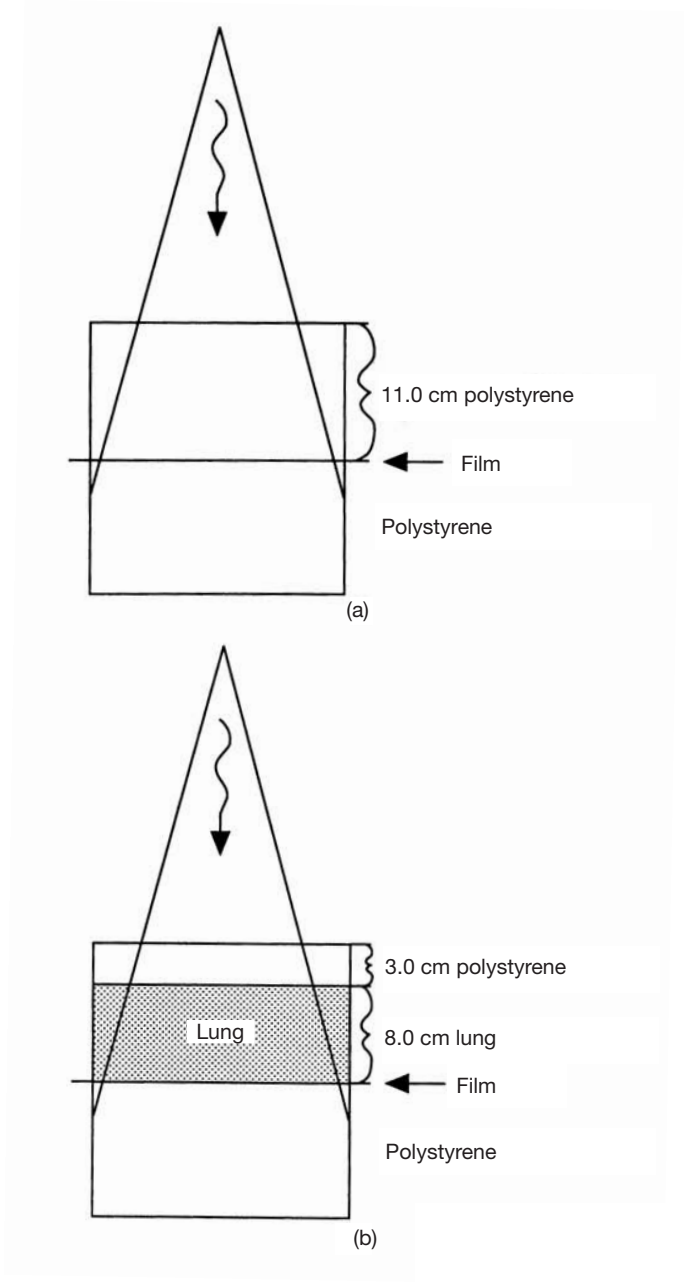

FIG. A–8. Phantom set-up for single field irradiations. Film is placed at the isocentre. (a) Polystyrene only, (b) lung phantom material and polystyrene. Reproduced, with permission, from Ref. [A–3].

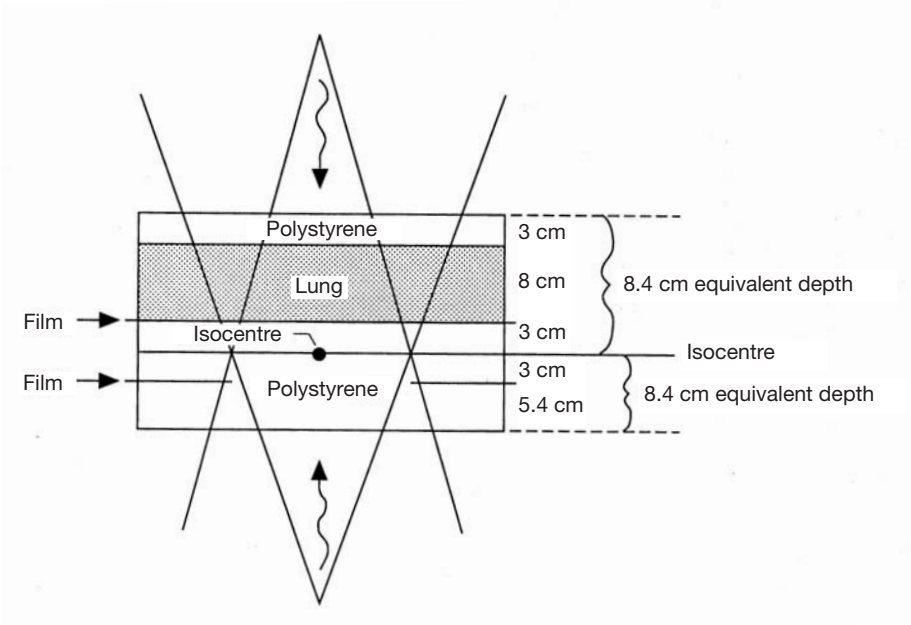

FIG. A–9. Phantom arrangement for parallel opposed irradiations. Films are placed 3 cm from the isocentre. In practice, the phantom is reversed between irradiations and the gantry is kept fixed to avoid the effects of mechanical distortions. Reproduced, with permission, from Ref. [A–3].

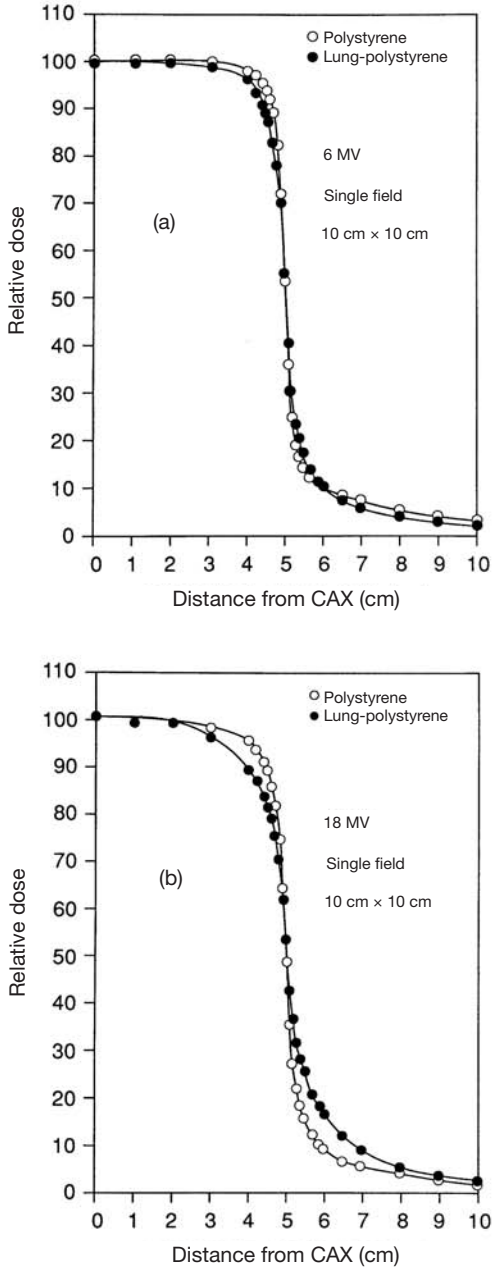

FIG. A–10. Half-beam profiles for single field irradiations. Open circles: polystyrene only, filled circles: lung–polystyrene interface. (a) 6 MV beam, (b) 18 MV beam. Reproduced, with permission, from Ref. [A–3].

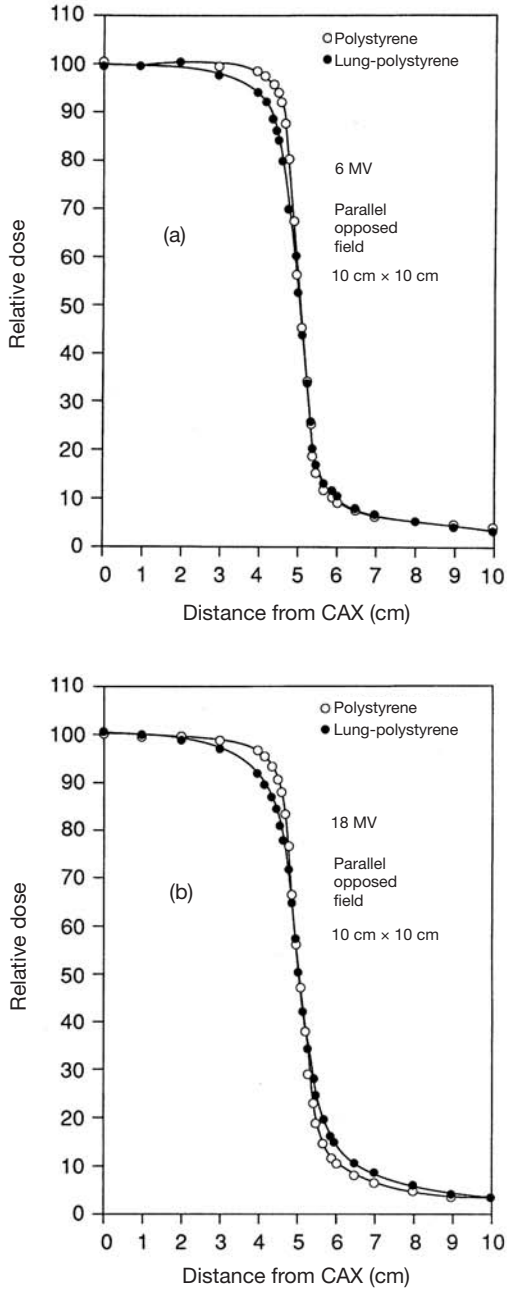

FIG. A–11. Half-beam profiles for parallel opposed irradiations. Open circles: polystyrene only, filled circles: lung–polystyrene interface. (a) 6 MV beam, (b) 18 MV beam. Reproduced, with permission, from Ref. [A–3].

TABLE A–1. ELECTRON COLLABORATIVE WORK GROUP TESTS

1. Basic standard geometry tests	Experiments 1–4 are standard baseline experiments: 6 × 6 and 15 × 15 field sizes using an SSD of 100 cm. Additional experiments 5–8 consist of the same field sizes and energies at an SSD of 110 cm. These eight experiments illustrate the basic fit between calculated and measured dose.			
	ECWG 1-1	9 MeV	15 × 15	100 SSD
	ECWG 2-1	9 MeV	6 × 6	100 SSD
	ECWG 3-1	20 MeV	15 × 15	100 SSD
	ECWG 4-1	20 MeV	6 × 6	100 SSD
	ECWG 5-2	9 MeV	15 × 15	110 SSD
	ECWG 6-2	9 MeV	6 × 6	110 SSD
	ECWG 7-2	20 MeV	15 × 15	110 SSD
	ECWG 8-2	20 MeV	6 × 6	110 SSD
2. Field shaping	Experiments 9–12 investigate the dose from various shaped fields.			
	ECWG 9-3	9 MeV	15 × 15 blocked to 3 × 12	
	ECWG 10-3	20 MeV	15 × 15 blocked to 3 × 12	
	ECWG 11-4	9 MeV	House block	
	ECWG 12-4	20 MeV	House block	
3. Cranio-spinal treatment fields	Experiment 13 simulates cranio-spinal treatments.			
	ECWG 13-5	20 MeV	25 × 25 blocked to 5 × 30	
	Diagonal at 110 SSD			
4. Small eye blocks	Experiment 14 tests a small circular radiation field (d = 5 cm) with a d = 1 cm eye block, as is often used in treatment of the orbit.			
	ECWG 14-6	20 MeV	5 cm diameter field with eye block	
5. Oblique incidence and irregular patient surfaces	Experiments 15–20 check the behaviour in non-perpendicular situations: oblique incidence, a step phantom and a ‘nose’ phantom.			
	ECWG 15-7	9 MeV	Oblique incidence	
	ECWG 16-7	20 MeV	Oblique incidence	
	ECWG 17-8	9 MeV	Step phantom	
	ECWG 18-8	20 MeV	Step phantom	
	ECWG 19-9	9 MeV	Nose simulation	
	ECWG 20-9	20 MeV	Nose simulation	

TABLE A–1. ELECTRON COLLABORATIVE WORK GROUP TESTS (cont.)

6. Heterogeneous phantoms	A slab inhomogeneity (chest wall cases) is tested in experiments 21–22. A long thin air inhomogeneity (neck or sinus) is tested in experiments 23–24. A similar bone inhomogeneity (rib, facial bones) is tested in experiments 25–26. A 3-D (L shaped) bone inhomogeneity is studied in experiments 27–28.		
	ECWG 21-10	9 MeV	Slab inhomogeneity
	ECWG 22-11	20 MeV	1/2 slab inhomogeneity
	ECWG 23-12	9 MeV	Linear bone inhomogeneity
	ECWG 24-12	20 MeV	Linear bone inhomogeneity
	ECWG 25-13	9 MeV	Linear air inhomogeneity
	ECWG 26-13	20 MeV	Linear air inhomogeneity
	ECWG 27-14	9 MeV	L shaped bone inhomogeneity
	ECWG 28-14	20 MeV	L shaped bone inhomogeneity

As for Ref. [A–3], these data cannot be used directly. Nevertheless the results obtained both at 6 MV and 18 MV give an indication of the type of changes expected in the penumbra region in the presence of an inhomogeneity.

REFERENCES TO THE ANNEX

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GLOSSARY

3-D conformal therapy (3-D CRT). Conformation of the high dose region to the target volume in 3-D, while minimizing dose to normal tissues (requires 3-D imaging and 3-D dose calculations).

absolute dose. Radiation dose with units of Gy or cGy.

acceptance. A user acknowledgement that the system satisfies the purchasing agreement and specifications.

acceptance testing. Tests performed to confirm that the system performs according to its purchase specifications.

algorithm. A method used for a calculation; the specific steps involved in the calculation.

algorithm implementation. The specific software used to perform the algorithm calculation.

algorithm input data. Data required by an algorithm.

attenuator. Material used to decrease the beam intensity, usually in a particular region (see also compensator).

automargin. Automatically or software created margin around a target; typically used when defining a block or MLC aperture.

basic beam data. Beam data for square fields at the standard SSD.

beam data acquisition system (BDAS). A water phantom equipped with a scanning detector (typically computer controlled).

beam model. The conceptual model used to create the dose distribution for a beam. The beam model is the basis for the algorithm that is coded into the software used for dose calculations.

beam normalization point. The point at which each individual beam's weight is defined. This point is often defined at d_{max} or at the isocentre of the beam.

beam weight. The dose (relative or absolute) defined at each individual beam's normalization point under given conditions. (Note that in some TPSs, 'beam weight' is only a relative strength and is not defined as precisely as this definition.)

beam's eye view (BEV). A 3-D projection of the patient anatomy and beam geometry, from the point of view of the source of the radiation.

benchmark data. Standard data, carefully measured or carefully calculated, which can be used for testing a dose calculation algorithm.

biologically equivalent dose (BED). The dose adjusted to give an equivalent biological effect at a certain fractionation (often 2 Gy/fraction).

bolus. Material, usually close to tissue equivalent, placed on the surface of the patient.

brachytherapy. Therapy in which radioactive sources are placed within or in close proximity to the tissue to be treated.

bulk inhomogeneity density corrections. Dose calculations corrected for density values assigned by the user to particular structures; not directly based on CT numbers.

clinical tests. Tests of TPS or dose calculations related to how the system will be used clinically.

collimation — jaws, MLCs and blocks. Devices that collimate the radiation beam on the way out of the head of the accelerator or ^{60}Co machine.

collimator setting. The size of the radiation field at a defined (standard) distance, typically at the isocentric distance.

commissioning. All testing, data input and verification checks that are needed to get the system ready for clinical use.

compensator, compensating filter. External device used to attenuate different regions of the beam by different amounts of material to cause a more uniform dose distribution inside the patient.

confidence limit, confidence interval, confidence level. Provides a degree of confidence in the statement of uncertainty associated with a particular measurement.

conformal field shaping (beam's eye view targeting). Conforming the shape of the irradiated field to the shape of the target in BEV.

contour. A closed curve that describes the intersection of an anatomical structure (typically) with the plane of an image.

co-ordinate system. Specification of the origin and directions of the co-ordinates used to describe objects.

DICOM. Digital Imaging and Communications in Medicine. A standard file format and transfer protocol for images (CT, MR, etc.).

DICOM-RT. An extension of the DICOM protocol that includes a description of radiation therapy treatment plan information (structures, beam parameters, dose, etc.).

digitizer. A device used to convert a measured shape (e.g. a contour) or image into a digital description that can be used by the computer.

digitally reconstructed radiograph (DRR). An image calculated from patient images (typically a CT set) that looks like a diagnostic or megavoltage film obtained for the same geometry of beam and patient.

d_{max}. The depth below the surface at which the central axis depth dose has a maximum.

documentation. A computer file or paper document that describes data or procedures.

dosimetrist. A specialist who performs radiation treatment planning with the TPS (could be a radiation therapist (radiographer or radiation therapy technologist) or a specially trained physicist).

dose–response curve. A curve describing how a particular organ or tumour responds to radiation (i.e. relative response versus dose).

dose–volume histogram (DVH). A histogram showing the number of voxels (i.e. volume or relative volume) of a structure that receives a given dose.

direct DVH. The most basic DVH: a frequency plot of the number of voxels receiving the dose specified in each dose bin.

cumulative DVH. Integration of the direct DVH: each point on the cumulative DVH gives the volume of the structure that receives at least the specified dose.

differential DVH. This is like the direct DVH, but the *y* axis (volume) values are divided by the dose bin size, in order to make the differential DVH independent of the dose bin size used for the histogram.

dosimetric data. Measured doses or distribution of doses.

dynamic therapy. Therapy delivered with the beam on while one or more of the machine parts, such as the gantry, collimator, MLC or couch, are moving.

dynamic wedge. Generation of a wedge shaped dose distribution using a moving collimator while the beam is on (see wedge).

electron density, relative electron density. Electron density is the number of electrons per unit volume, while the relative electron density is the electron density for a particular medium divided by the electron density for water. This is important for dose calculation and is typically obtained from CT information.

electronic equilibrium. When the same number of electrons are set in motion in a given small volume as come to rest in the same volume.

electronic transfer. Transfer of computer files from one system to another.

error. In general, a wrong action or procedure, although the term is sometimes loosely used to describe deviations from the expected value.

ethernet. Hardware networking protocol used for high speed links between computers.

field size. Different TPSs (and treatment systems) define 'field size' in two different ways. Some systems will define the field size as the size of the radiation field at some distance in the patient, which means that the size of the radiation field at the isocentre changes with the location of the patient. More modern systems typically define the field size to be identical with the collimator setting that defines the field size at the isocentre.

generic data. General data that are not specific to an individual machine but that are generally descriptive of a beam of a particular energy.

hard copy. A paper report or graphic output.

hardware. Computer equipment.

image. Picture type information. In this context, usually a CT, MR or other diagnostic scan, or a digital film.

image registration. The geometric relationship between two sets of images.

inhomogeneity corrections. Dose calculation corrections that incorporate the effects of differing density of tissues within the patient. It is a correction applied to a water-like calculation.

intensity modulated radiotherapy (IMRT). The use of beams that have modulated intensities (the intensity of the beam is different in different regions of the beam). IMRT beams are often generated using inverse planning procedures.

input data. Data required by a computer program.

inverse planning. A type of planning often used for IMRT, in which the dosimetric goals of the planning are stated initially and the planning system then automatically generates the plan that 'best' (or at least adequately) satisfies the stated goals.

in vitro. 'In glass', commonly involving cells in an artificial container. In this context, dosimetry in a phantom.

in vivo. 'In life'. In this context, dosimetry in the patient.

level. An in-image display; the numerical value that is the centre of the displayed grey scales.

mantle fields. Large irregularly shaped thoracic or abdominal fields used to treat Hodgkin's disease.

medical physicist. A physicist trained in radiation oncology, radiology and/or nuclear medicine.

Monte Carlo calculation. A dose calculation method based on nuclear physics interactions of particles, in which millions or billions of particle histories are tracked to estimate the behaviour of a real radiation beam.

multileaf collimator (MLC). A machine collimation system that incorporates a set of computer controlled leaves that allow the creation of user defined beam apertures.

multiplanar reconstruction. A picture incorporating images projected into a 3-D view.

model. A conceptual design for dose calculations, beam description and equipment description.

model fitting. A method for defining calculation parameters so that the dose calculation results agree well with measurements.

monitor unit (MU). A numerical value, set on a treatment machine, proportional to the beam intensity through the accelerator collimation system. MUs are typically calibrated to define the dose delivered to the patient under reference conditions.

network. Interconnection of a number of computers.

normal tissue complication probability (NTCP). The probability that a given dose distribution will cause a specific complication in a given organ. Also used to describe a specific model for NTCP that was introduced by Lyman[1].

normalization. A method for rescaling a dose distribution to give a specified value at a defined normalization point.

non-dosimetric data. Parameters of the TPS that are not related to dose distributions (e.g. definition of field size or shape or the angle co-ordinate system used for the gantry angle).

overall plan normalization. Renormalization of the dose distribution to give a chosen (absolute or relative) dose at the plan normalization point (e.g. set dose = 100%, or 1.8 Gy, or 60 Gy at the plan normalization point).

parameterization. The set of parameters (numbers) required by a model to give a good description of the process being modelled.

penumbra. The region of the beam at which only part of the source is seen: typically the penumbral width is defined as the edge of the beam from 80% of the central value of the beam to 20% of the value.

periodic quality assurance. QA tests performed at regular time intervals.

peripherals. Computer devices such as printers or digitizers that are distinct from the main computer (CPU, hard disks and memory).

phantom. Material used for in vitro dose measurements, such as water or solid water or an anthropomorphic phantom (resembling a human).

pixel. 'Picture element'. A 2-D element of a digital image.

plan normalization point (isodose reference point). A point (3-D co-ordinates) at which the overall plan normalization is defined.

plan transfer. Moving the treatment plan information from the TPS to any other device.

profile. In dosimetry, the dose measured along a line, typically across a beam.

quality assurance (QA). Planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy the given requirements for quality[2].

quality control (QC). The regulatory process through which the actual quality performance is measured, compared with existing standards, and the actions necessary to keep or regain conformance with the standards[2].

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[1] LYMAN, J.T., Complication probability as assessed from dose–volume histograms, Radiat. Res. Suppl. 8 (1985) S13–S19.

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management and Quality Assurance Standards, Part 1: Guidelines for Selection and Use, ISO 9000, ISO, Geneva (1994).

radiation oncologist. A medical doctor specializing in radiation therapy of cancer patients.

radiation oncology management system. An information system used for radiation oncology scheduling, patient treatment delivery, information archiving, etc.

radiation therapy technologist. A treatment technologist, radiation therapist, medical radiation therapist, radiographer or technician.

radiation treatment planning system. A device, usually a programmable electronic system, that is used to simulate the application of radiation to a patient for a proposed radiotherapy treatment. In this context, usually a treatment planning system (TPS): hardware, the computer operating system and TPS software.

radiosurgery. A single fraction (or few fraction) treatment in which the target is localized with high precision using specific hardware (typically a rigid frame physically attached to the patient).

recommissioning. Rechecking the behaviour of the TPS after hardware replacement and software updates or upgrades.

reconstructed image. An image created from CT or other images, but in a different plane than that in which the original data were obtained.

redundancy check. Confirmation that two methods of determining the answer give the same result.

reference air kerma rate. The kerma rate to air, in air, at a reference distance of 1 m after correction for air attenuation and scattering; used to specify the strength of a radioisotope source.

reference data. Data used as reference for individual system or calculation checks.

relative dose. Dose distribution displayed in per cent, relative to the dose at a particular point under defined conditions.

slice. A planar image.

software. Computer instructions or code.

solid water. Epoxy-like material that has a very similar density and beam absorption characteristics to liquid water. Sometimes the term is loosely used to describe other similar commercial products (plastic water, white water, etc.).

specifications. A description of the limits within which a piece of equipment is supposed to work or achieve the correct answer.

stereotactic. Use of a 3-D fixed co-ordinate system to locate internal anatomy (see also radiosurgery).

structure. A 3-D anatomical object used in a TPS, typically corresponding to an organ or a target for radiation therapy.

surface. The skin of the patient.

surface description. The 3-D mesh that describes the 3-D shape of an object for the computer.

system software. Computer operating system software and associated ancillary vendor supplied software (drivers, etc.).

target volume. A 3-D object that is the intended target for the high dose part of the dose distribution. The following volumes are defined in ICRU Rep. 50[3].

GTV (gross tumour volume). The tumour that is visible on imaging data (e.g. in CT).

CTV (clinical target volume). The 3-D object describing the region that the physician wants to treat. Usually includes the GTV.

PTV (planning target volume). The 3-D object describing the region that should be planned to receive a high dose. This is typically an expansion of the CTV to compensate for patient set-up errors and organ motion.

tender document. A document used to propose the requirements for the purchase of a TPS.

tertiary blocking. Blocking or shielding items placed close to the patient, below the machine collimation system.

tolerance. A description of variations that are acceptable.

total quality management (TQM). That aspect of the overall management function that determines and implements the quality policy and, as such, is the responsibility of senior management[4].

treatment planner. Someone who uses the treatment planning computer to generate treatment plans. Could be a radiation oncologist, physicist, dosimetrist or trained radiation therapist.

tumour control probability (TCP). The probability that a given dose distribution will cause a tumour control.

uncertainty. A parameter that characterizes the dispersion of values that can be obtained for a particular measurement when it is performed repeatedly.

update. An improved version of software or hardware (typically fixing problems).

upgrade. More significant improvement in software or hardware (typically including new functionality).

vendor. A company that sells a product such as a TPS system, TPS software or hardware.

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[3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Prescribing, Recording, and Reporting Photon Beam Therapy, Rep. 50, ICRU, Bethesda, MD (1993).

[4] ZAIRI, M., Total Quality Management for Engineers, Gulf Publishing, Houston, TX (1993).

virtual simulation. Software that mimics the actions of a radiation therapy simulator.

voxel. 'Volume element'. The basic building block of a volumetric description of an object.

wedge. A metal wedge shaped absorber (physical, hard, mechanical) placed in the beam path to produce a dose gradient across the field. Can be motorized (automatic or flying wedge). A similar effect can be achieved by movement of one jaw (dynamic or virtual wedge).

window. In image display, the difference between the limiting numerical values that the grey scale represents.

ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
AP	anteroposterior
BDAS	beam data acquisition system
BEV	beam's eye view
CIPM	Comité international des poids et mesures (International Committee of Weights and Measurements)
CPU	central processing unit
CRT	conformal radiation therapy
CT	computed tomography
DICOM	Digital Imaging and Communications in Medicine
DRR	digitally reconstructed radiograph
DVH	dose–volume histogram
ECWG	Electron Collaborative Work Group
FTP	file transfer protocol
HBI	half-body irradiation
HDR	high dose rate
ICRP	International Commission on Radiation Protection
ICRU	International Commission on Radiation Units and Measurements
IDL	isodose line
IEC	International Electrotechnical Commission
IMRT	intensity modulated radiation therapy
LDA	linear detector array
LDR	low dose rate
MLC	multileaf collimator
MOSFET	metal oxide semiconductor field effect transistor
MR	magnetic resonance
MRI	magnetic resonance imaging
MU	monitor unit

NTCP	normal tissue complication probability
OAR	off-axis ratio
PA	posteroanterior
PDD	percentage depth dose
PDR	pulsed dose rate
PET	positron emission tomography
QA	quality assurance
QC	quality control
SAD	source to axis distance
SAR	scatter air ratio
S_c	collimator scatter factor
S_p	phantom scatter factor
SPECT	single photon emission tomography
SSD	source to surface distance
TAR	tissue air ratio
TBI	total body irradiation
TCP	tumour control probability
TPS	treatment planning system
TQM	total quality management
TLD	thermoluminescence dosimetry
TSEI	total skin electron irradiation

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