IAEA HUMAN HEALTH REPORTS No. 18

National Networks for Radiotherapy Dosimetry Audits

Structure, Methodology, Scientific Procedures

IAEA
International Atomic Energy Agency

IAEA HUMAN HEALTH SERIES PUBLICATIONS

The mandate of the IAEA human health programme originates from Article II of its Statute, which states that the "Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". The main objective of the human health programme is to enhance the capabilities of IAEA Member States in addressing issues related to the prevention, diagnosis and treatment of health problems through the development and application of nuclear techniques, within a framework of quality assurance.

Publications in the IAEA Human Health Series provide information in the areas of: radiation medicine, including diagnostic radiology, diagnostic and therapeutic nuclear medicine, and radiation therapy; dosimetry and medical radiation physics; and stable isotope techniques and other nuclear applications in nutrition. The publications have a broad readership and are aimed at medical practitioners, researchers and other professionals. International experts assist the IAEA Secretariat in drafting and reviewing these publications. Some of the publications in this series may also be endorsed or co-sponsored by international organizations and professional societies active in the relevant fields.

There are two categories of publications in this series:

IAEA HUMAN HEALTH SERIES

Publications in this category present analyses or provide information of an advisory nature, for example guidelines, codes and standards of practice, and quality assurance manuals. Monographs and high level educational material, such as graduate texts, are also published in this series.

IAEA HUMAN HEALTH REPORTS

Human Health Reports complement information published in the IAEA Human Health Series in areas of radiation medicine, dosimetry and medical radiation physics, and nutrition. These publications include reports of technical meetings, the results of IAEA coordinated research projects, interim reports on IAEA projects, and educational material compiled for IAEA training courses dealing with human health related subjects. In some cases, these reports may provide supporting material relating to publications issued in the IAEA Human Health Series.

All of these publications can be downloaded cost free from the IAEA web site:

http://www.iaea.org/Publications/index.html

Further information is available from:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria

Readers are invited to provide their impressions on these publications. Information may be provided via the IAEA web site, by mail at the address given above, or by email to:

Official.Mail@iaea.org.

NATIONAL NETWORKS FOR RADIOTHERAPY DOSIMETRY AUDITS STRUCTURE, METHODOLOGY, SCIENTIFIC PROCEDURES

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
COMOROS
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GAMBIA
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT KITTS AND NEVIS
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAMOA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TONGA
TRINIDAD AND TOBAGO
TUNISIA
TÜRKİYE
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA HUMAN HEALTH REPORTS No. 18

NATIONAL NETWORKS FOR RADIOTHERAPY DOSIMETRY AUDITS

Structure, Methodology, Scientific Procedures

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2023

COPYRIGHT NOTICE

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

Printed by the IAEA in Austria
June 2023
STI/PUB/1964

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: National networks for radiotherapy dosimetry audits : structure, methodology, scientific procedures / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2023. | Series: IAEA human health reports, ISSN 2074–7667 ; no. 18 | Includes bibliographical references.
Identifiers: IAEAL 23-01580 | ISBN 978–92–0–130921–1 (paperback : alk. paper) | ISBN 978–92–0–131021–7 (pdf) | ISBN 978–92–0–131121–4 (epub)
Subjects: LCSH: Radiotherapy — Quality control. | Radiotherapy — Safety measures. | Cancer — Treatment. | Radiation dosimetry.
Classification: UDC 615.849 | STI/PUB/1964

FOREWORD

In recent years, the global incidence of cancer has risen significantly. According to the World Health Organization (WHO), nearly one in six deaths is due to cancer or cancer is the second leading cause of death worldwide. Close to 50% of cancer patients need radiation treatment. The radiation dose received by the tumour has to be precisely prescribed by the physician, as too much radiation will damage healthy tissue, whereas too little will not effectively treat cancer cells. Quality assurance (QA) in radiotherapy dosimetry is essential in this respect and contributes to ensuring that accurate radiation doses are delivered during patient treatment. Independent quality audits constitute part of such QA programmes and can be used to ensure that the quality of dosimetry practices in a radiotherapy centre is suitable for achieving the patient treatment objectives. Quality audits are effective in identifying problems in clinical dosimetry. They can bring such problems to the attention of medical physicists and help to find the problems' causes and to resolve the problems. Dosimetry audits have been advised by both the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, and the European Basic Safety Standards.

The IAEA has a long-standing history of providing radiotherapy dosimetry audits in various countries across the world. The joint IAEA/ World Health Organization (WHO) postal dose audit service has been in operation for five decades. Many discrepancies in radiotherapy dosimetry have been discovered and rectified, resulting in better accuracy in clinical dosimetry. To extend the availability of dosimetry audits to as many radiotherapy centres as possible throughout the world, the IAEA supported the development of methodologies and helped establish several national QA audit networks. A series of four coordinated research projects (CRPs) were conducted by the IAEA between 1995 and 2017 to assist in developing such national programmes for remote dosimetry audit, primarily using thermoluminescent dosimetry. The overall radiotherapy dosimetry audit approach established and developed throughout these CRPs is based on a process of increasing the complexity of audit steps, from simple to advanced techniques, so that the experience of previous steps is used to inform the development, implementation and analysis of results for subsequent audit steps. Altogether, 11 audit methodologies were developed, tested and implemented internationally, which explains the wide time frame covered in this publication.

This publication summarizes the methodologies developed under the four CRPs and offers information on experiences collected during the development of dosimetry audit programmes and their implementation at national levels. It also sets the framework and provides advice on the structure of dosimetry audit centres and discusses the general approach for audit development and the necessary background to conduct dosimetry audits in radiotherapy by national organizations. It provides technical and scientific details, as well as practical experiences of the audit steps developed under these CRPs. Any organization willing to develop national audit programmes for radiotherapy can use this publication as reference material and learn from the experiences of other national audit networks.

The on-line supplementary files for this publication, which can be found on the publication's individual web page at www.iaea.org/publications, include examples of the radiotherapy infrastructure questionnaire, dosimetry audit instruction sheets, data sheets and results reporting forms.

The IAEA acknowledges special contributions to the development of methodologies for dosimetry audits in radiotherapy within four CRPs by A. Dutreix (France), D. Followill (United States of America), D. Georg (Austria), and D. Thwaites (United Kingdom). The IAEA officer responsible for this publication is J. Izewska of the Division of Human Health.

EDITORIAL NOTE

This publication has been edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance. It does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.

Although great care has been taken to maintain the accuracy of information contained in this publication, neither the IAEA nor its Member States assume any responsibility for consequences which may arise from its use.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA has no responsibility for the persistence or accuracy of URLs for external or third party Internet web sites referred to in this book and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

CONTENTS

1. INTRODUCTION 1

1.1. Radiotherapy provision for cancer treatment 1
1.2. Accuracy required in radiotherapy 1
1.3. QA in radiotherapy 2
1.4. Discrepancies in radiation treatment 3
1.5. The need for independent quality audit in radiotherapy generally and in radiotherapy dosimetry 4
1.6. IAEA and other approaches to independent quality audit of radiotherapy dosimetry . . 5
1.7. Extension of the scope of radiotherapy dosimetry audit within the IAEA framework. . 7
1.8. Scope of the publication 7

2. OVERVIEW OF COORDINATED RESEARCH PROJECTS ON DOSIMETRY AUDIT IN RADIOTHERAPY 8

2.1. Overview of the framework of the development of the audits 8
2.2. Overview of the process for the development of audits 11

3. GUIDELINES FOR ESTABLISHING A NATIONAL DOSIMETRY AUDIT NETWORK FOR RADIOTHERAPY 13

3.1. Introduction 13
3.2. Aim of the DAN 13
3.3. National radiotherapy infrastructure database. 13
3.4. Structure of the DAN 14
3.5. DAC development and operations 14
3.6. DAC audits and required resources 15
3.7. Summary 16

4. AUDIT STEPS — METHODOLOGY AND TESTING 17

4.1. Step 1: TLD audits for photon beams in reference conditions 17
4.2. Step 2a: TLD audits for photon beams in non-reference conditions 21
4.3. Step 2b: TLD audits for electron beams in reference and non-reference conditions on the beam axis 26
4.4. Step 3: Audits for photon beams in reference conditions and non-reference conditions off-axis. 29
4.5. Step 4: Dose audits of complex treatment technique parameters: irregular photon beams shaped with an MLC 43
4.6. Step 5: Audits of complex treatment parameters for photon beams; situations involving heterogeneities 48
4.7. Step 6: Audits of complex treatment parameters: small photon fields shaped by an MLC 53
4.8. Step 7a: Quality audits of output factors of small fields shaped with MLC. 63
4.9. Step 7b: Film quality audit of MLC performance for IMRT dose delivery. 71
4.10. Step 8: Film quality audit for relative dosimetry of a photon beam single IMRT field . 80

4.11. Step 9: ‘End-to-end’ dosimetric quality audit for IMRT, including imaging, treatment planning and delivery 85

5. CONCLUSION 94

APPENDIX I: CHARACTERISTICS OF TLD SYSTEMS OF DOSIMETRY AUDIT CENTRES 97

APPENDIX II: CHARACTERISTICS OF THE FILM DOSIMETRY SYSTEM 109

REFERENCES 113
LIST OF ABBREVIATIONS 121
ANNEX: SUPPLEMENTARY FILES 123
CONTRIBUTORS TO DRAFTING AND REVIEW 125

1. INTRODUCTION

1.1. RADIOTHERAPY PROVISION FOR CANCER TREATMENT

Cancer is a rapidly increasing problem across the world. It has been estimated by the Global Cancer Observatory of the World Health Organization (WHO) that cancer incidence will increase from 18 million cases in 2018 to 30 million in 2040 [1]. In 2018, there were approximately 10 million cancer deaths, 70% of which were in low and middle income countries [2–4].

Radiotherapy is one of the major modalities for cancer treatment, along with surgery and chemotherapy. The 2014 World Cancer Report [3] states that "radiotherapy is fundamental to the optimum management of cancer patients, and provision of radiotherapy services is central to national cancer control strategies". The report recognizes that effective radiotherapy for many cancers can be comprehensively provided at moderate cost, although long term planning and appropriate assessment of health care resources are required. Radiotherapy is practical, on its own or in combination with one of the other modalities, such as surgery or chemotherapy, in approximately 50% of cancer cases [5, 6], but its application is often limited by lack of appropriate equipment, trained staff or other necessary resources. Radiotherapy is a major modality in curative treatment of cancers, but also plays a very significant role in palliative cancer strategies. It is known from the IAEA's world Directory of Radiotherapy Centres (DIRAC) [7] that there are currently less than half the necessary number of megavoltage radiotherapy machines in low and middle income countries, leaving a deficit of more than 3000 machines, and that the necessary number will at least double by 2030 in line with the projected rise in cancer incidence [8].

According to generally accepted estimates, approximately 45% of cancer patients are curable at present, using an appropriate combination of all treatment modalities. However, this cure rate cannot be achieved unless the following are implemented:

— There is a sufficient infrastructure;
— There is consistent and appropriate integration and use of the different treatment modalities;
— High quality processes and procedures are maintained.

1.2. ACCURACY REQUIRED IN RADIOTHERAPY

For radiotherapy, high degrees of accuracy, reliability and reproducibility are necessary [9]. This is the case both for the overall levels of dose delivered to a tumour and for the relative dose distribution around and across the tumour and its spatial position, to ensure adequate dose coverage of the targeted volumes. In addition, equally detailed consideration is needed regarding the dose distribution and its spatial position relative to nearby normal organs and tissues, as radiotherapy is always a careful and critical balance between achieving the needed effect on the tumour and limiting the effect on normal tissues to within acceptable levels.

It is well known that the biological effect of radiation on tumours and normal tissues acts according to sigmoid-shaped dose–response relationships. Clinical dose–response curves for tumour control probability and normal tissue complication probability are recognized to vary in steepness, but typically a 5% change in dose results in a 10–30% change in response when looking at the steepest portion of such curves. Therefore, even small uncontrolled changes in dose may significantly change the achieved tumour control probability or normal tissue complication probability compared to the clinically expected result. Statements about the required accuracy in radiation treatment are based on the steepness of such dose–response relationships and also on what accuracy is achievable in practice when the many stages and parameters involved in the radiation treatment process are taken into account. On the basis of these considerations, in 1976 the International Commission on Radiation Units and Measurements advised

that the overall accuracy in the radiation dose delivered to the dose specification point in the patient be 5% [10]. More recent analyses of accumulating clinical data have been in reasonable agreement with this value [8, 9]. Besides recommendations on the required dosimetric accuracy, there are also consistent recommendations on geometric accuracy [11, 12], as changes in the spatial position of dose delivery will result in dosimetric changes, either by producing potential misses of parts of the tumour or by delivering more dose to nearby normal tissues than was intended.

In summary, the recommended accuracy of dose delivery is generally given as 5–7% (at the $k = 2$ expanded uncertainty or 95% confidence level, depending on the factors intended to be included [9]. Values of 5–10 mm (95% confidence level) have been given for spatial accuracy. Note that these are general requirements for routine clinical practice, and in specific specialist applications better accuracy might be necessary and demanded (e.g. in stereotactic treatments, image guided methods, dose escalation situations). For example, it may be noted that more recent summaries have considered whether new technology, techniques or clinical information have changed these requirements [9, 13]. In general, the dose requirements are still applicable, but increasing use of image guidance techniques has reduced the recommended tolerances on geometric accuracy in appropriate circumstances. The general recommendations on accuracy requirements are for the end point of the radiotherapy process (i.e. for the treatment as delivered to the patient). Therefore, in each of the many steps of the complex radiotherapy process that contribute to its final accuracy, correspondingly smaller values are necessary, such that when all are combined the overall accuracy is met. Thus, quality control tolerances on individual parameters in the process are often of the order of 1%, 1 mm, etc. [9, 13, 14].

There have been a number of assessments of the accuracy that is estimated to be achievable in radiotherapy under optimized conditions [9, 13, 15]. These have shown that the necessary levels are difficult to achieve and need very careful attention to be paid to every aspect of the radiotherapy process, with each step, parameter and procedure subject to ongoing quality assurance (QA). The approach to QA and to the level of detail and control required have to be consistent between the different activities [16–19], in particular between those of radiation oncologists, physicists and radiation therapy technologists (often also termed therapy radiographers, radiation therapists, radiation technologists, radiation nurses, etc.). Reported evidence, from the checking of treatment delivery within particular centres by in vivo dosimetry, from external audit system measurements of doses in different centres (see Section 1.6) and from reports of radiation misadministrations (see Section 1.4), all indicates that conditions are not always optimized, leading to yet further emphasis on the need for QA and quality management.

It may be noted that the introduction and development of techniques such as intensity modulated radiotherapy (IMRT) and image guided radiotherapy, as well as the increasing use of stereotactic methods, adaptive radiotherapy techniques and other advanced technology, potentially enables and also demands greater accuracy, and this could lead to reduced target margins and dose escalation. Therefore, at the same time, these techniques need greater QA effort. It is possible that this could in turn lead to a re-evaluation of accuracy recommendations and requirements in the future, as treatment techniques develop further based on their availability [9, 13].

1.3. QA IN RADIOTHERAPY

Detailed and continuing QA of the radiotherapy process is necessary to achieve the required level of accuracy and maintain it consistently. More widely, it is necessary to ensure high and continued quality in radiation treatment for all patients. To optimize clinical outcomes, it is equally important that the clinical aspects (i.e. diagnosis, decision making, indication for treatment, decisions on what to include in target volumes, decisions on criteria for limiting dose to organs at risk, follow-up, etc.), as well as the physical and technical aspects of patient treatment, have to be subject to careful control and planning. Comprehensive QA programmes (or quality management systems) should be established to cover all steps from treatment decision and prescription right up to dose delivery and follow-up [9, 11, 12, 15–17, 20–24], and there is a wide range of national and international QA recommendations

and guidelines that provide details of procedures, quality control tests and tolerances for many parts of the process [25–29].

Besides maintaining accuracy and reproducibility, ongoing QA is also necessary, in part to minimize the possibility of radiation incidents affecting patient safety. This is particularly important for radiotherapy, as it is a high dose procedure and therefore potentially a high risk procedure, and overdoses can cause significant damage to organs and tissues. On the other hand, a significant underdose can cause failure to control disease. Note that underdoses in radiotherapy are just as important for the overall quality of treatment outcome as overdoses, whereas in a radiation protection context only overdoses are normally considered to be of significance.

The aim of a QA programme is to maintain each individual step within an acceptable tolerance. Very careful attention is necessary at all levels and for each part of the process and each substage within these parts. The more complex the treatment technique, the more stages, substages, parameters and factors are involved, and correspondingly more complex QA procedures are necessary.

The fact that high accuracy and quality is critically necessary for good, safe and reproducible radiotherapy and that more complex types of treatment need more complex QA, implies consequences if resources are limited. It is more important to ensure high accuracy and quality in existing treatments first, before implementing more complex treatment methods and techniques. In fact, without existing and demonstrated high accuracy from careful and consistent QA programmes, the more complex treatment techniques can give more problems in treatment. Thus, it can be better for patients' treatment outcomes to give less complex treatments, but with good QA, than to give more complex treatments with poorer QA. Thus, where there are discussions of priorities in cases where resources may be limited, it is suggested to put effort first into improving the QA of existing, less complex treatment methods and techniques, rather than into implementing newer highly complex treatments. Only when the former are of high quality and accuracy, demonstrated by internal verification and checks and by external audits, should the more complex approaches be considered for implementation. These will need adequate staffing of all the relevant qualified professional groups, including radiation oncologists, medical physicists and radiation therapy technologists, and will also need specific training to be provided in these newer technologies and methods [30–32].

1.4. DISCREPANCIES IN RADIATION TREATMENT

Cases occur where discrepancies have been reported during radiation treatment or where the possibility of discrepancies may be indicated from measurement or observation of part of the radiotherapy process despite the widespread recommendations for QA. For example, the International Commission on Radiological Protection, the American Society for Therapeutic Radiology and Oncology and the IAEA [18, 33–37] have analysed a wide range of accidental exposures during radiotherapy to draw lessons on methods for the prevention of such occurrences. Discrepancies between the delivered and intended treatment in the context of QA activities have been identified and have therefore been rectified. These have been of various magnitudes below the level of accidental exposure, including 'near misses'. Their causes have been catalogued to help others review their QA programmes. There are several examples reported in the literature of suboptimal dosimetry practices, including evidence from in vivo dosimetry programmes, dosimetry audits and inter-institutional comparisons, radiotherapy treatment chart reviews, planning calculation checks, etc. [11, 35, 38–43].

A number of general observations can be made in any wide-ranging analysis of near misses. Errors may occur at any stage and be made by any staff group. The major cause of a large proportion of discrepancies is human error. In addition to the direct causes of errors, there are a number of general contributing factors, including but not limited to complacency, a lack of knowledge or experience, overconfidence, time pressures, lack of resources, lack of staff, failures in communication, challenges with information or communication interfaces between staff groups or systems (i.e. where information is transferred across boundaries between one staff group and another, from one system to another or from

one part of the process to another). Most of the direct and contributing causes of discrepancies in radiation treatment are also compounded by the lack of an adequate QA, a quality management programme or a failure in its application. Errors in any human activity are always possible, including radiotherapy. However, a comprehensive, systematic and consistently applied QA programme, within the context of a structured quality system or quality management system [17, 21, 22, 44], has the potential to minimize the number of occurrences and also to identify them at the earliest possible opportunity when they do occur, thereby also helping to minimize their consequences for patient treatment. Such QA systems need to include a multilayered approach to ensuring quality. Increasingly, these are also including methods adapted from industry, such as statistical process control, failure mode and effects analysis [45–50].

1.5. THE NEED FOR INDEPENDENT QUALITY AUDIT IN RADIOTHERAPY GENERALLY AND IN RADIOTHERAPY DOSIMETRY

It is widely recognized that a comprehensive QA programme should include not only detailed quality control checks performed by each radiotherapy centre on all its systems, procedures and activities, but also quality audits [9, 11–14, 21, 22, 24, 44, 51–53]. Independent external audit is clearly recognized as an effective method of checking that the quality of activities in an individual institution is suitable for achieving the required objectives [54–66]. Various international radiation protection guidances [15–18, 33, 51, 67] also advise an audit as a necessary component of ensuring the safety of medical radiation uses.

Quality audits vary widely based on types and levels and review whole processes or specific critical parts of them. For example, the IAEA established a system called the Quality Assurance Team for Radiation Oncology (QUATRO) to enable multidisciplinary teams to carry out one-off on-site comprehensive audits of the whole radiotherapy structure and process of a department and has produced guidelines for this overall audit approach [21]. Within the QUATRO framework there are also specific guidelines for the on-site audit of the whole of a department's medical physics processes [21, 44]. More focused audits may concentrate on specific radiotherapy dosimetry parameters, an area where there is a long history of independent external audit, such as the long standing IAEA/WHO mailed dosimetry audit service [38, 66, 68–70]. Quality audits may be *proactive* (i.e. focused on the routine review of ongoing procedures with the aim of improving the quality of the process and preventing or minimizing the probability of errors and accidents) or they may be *reactive* (i.e. focused on the response to a suspected or reported incident). Examples of proactive and reactive quality audits are, respectively, the IAEA/WHO mailed dose programme [38, 70] or routine on-site review visits of radiotherapy institutions by IAEA experts [21] and specific on-site review visits to investigate particular occurrences [36, 37]. Quality audit testing and review can aid in providing advice on improvements in practice, where appropriate [21].

Quality audit is necessary to close the QA loop by testing whether the QA activity at the local radiotherapy centre (LC) has been appropriately and effectively implemented, and whether it does ensure the delivery of what is intended. It provides independent assessments of methods, procedures, processes and data and can verify the effectiveness, or performance, of the QA programme. It can identify problems so that they are rectified. Therefore, it aids in reducing uncertainties and increasing the consistency of radiotherapy between centres, and hence consistency in radiotherapy results and outcomes. Audits improve practice over time; it is the experience of all reported audit systems that performance gradually improves in later subsequent audits compared with the earlier rounds, partly because errors identified earlier are rectified and partly because audits give an impetus to departments to focus on quality and performance [59, 63, 70]. Audits can reduce the likelihood of accidents and errors occurring and continuing, thereby reducing adverse consequences for patient treatment. This is true for general radiotherapy quality audits and also, in the context of the current publication, for radiotherapy dosimetry audits. Audit can also provide support and confidence for the introduction of new and complex processes and technologies [55, 64, 71] and act as an aid to the education of staff in the audited centres [59]. It has to be noted that external audits are *not* a substitute for any part of the LC's QA programme but are an addition to it.

1.6. IAEA AND OTHER APPROACHES TO INDEPENDENT QUALITY AUDIT OF RADIOTHERAPY DOSIMETRY

A number of national or international bodies have developed various types and levels of external audits for radiotherapy dosimetry. Mostly, audits are conducted nationally, with a few organizations providing audit services internationally. These include the IAEA/WHO [38, 66, 69, 70]; the Imaging and Radiation Oncology Core Houston QA Center (formerly the Radiological Physics Center; (IROC-H) together with the Radiation Dosimetry Service (RDS), both based in Houston, Texas, United States of America; and Equal-Estro [72, 73], a QA network for radiotherapy (Equal) set up by the European Society for Therapeutic Radiology and Oncology (ESTRO) in Villejuif, France. These centres make available external audits to any radiotherapy centre within their remit on a regular basis, using mailed dosimeters. The IAEA annually delivers audits to radiotherapy centres in 60–70 countries, the IROC-H with RDS delivers audits to about 60 countries and Equal-Estro delivers audits to about 40 countries [63]. IROC-H was set up to support clinical trials [71, 74–76] and is funded by the US National Cancer Institute, so in effect provides a routine service, mainly in North America. It is the largest such operation, currently monitoring around 20 000 radiotherapy beams per year in more than 2300 radiotherapy centres. It also operates external audits for complex treatment techniques and on-site measurement audits [40, 71, 75, 77–79]. Other currently operating external audit programmes have used mailed dosimeters, on-site visits or a combination of these [60–66, 68, 80]. They have been either one-off national dosimetry inter-institutional comparison exercises, carried out to test various levels of radiotherapy dosimetry at a specific time, or they are ongoing regular national audit systems of dosimetry at varying levels [55, 59, 61–64, 81–85]. Some are linked with varying degrees of formality to national cancer control regulations and to the comprehensive audit of radiotherapy centres, including QA programmes, equipment and dosimetry (e.g. the United Kingdom's audit programme) [59]. Some have been associated with international or national clinical trial groups, and their audits are in support of general dosimetry infrastructure for entry to clinical trials and also specifically in support of individual trials (e.g. in Europe, the European Organization for Research and Treatment of Cancer; in North America and more widely, IROC-H, funded by the National Cancer Institute; and in the United Kingdom (UK), the National Cancer Research Institute coordinated Radiotherapy Trials QA Group (RTTQA)).

It may be noted that all three main audit systems mentioned above, as well as others, were initially established using mailed thermoluminescent dosimeters (TLDs) as the measurement method [69, 70, 72, 74, 76, 86–88]. However, it may be noted that more recently they have also considered and/or adopted other systems in addition to, or instead of, TLDs. Thus, IROC-H transferred its dosimetry system from TLDs to optically stimulated luminescence dosimeters (OSLDs) for its routine service [77] in 2010; and the IAEA investigated OSLDs and radiophotoluminescence (glass) dosimeters (RPLDs) and decided to adopt RPLDs for radiotherapy audit measurements [89]. In addition, several audit systems have begun to investigate or have already implemented other measurement methods for two dimensional (2-D) and three dimensional (3-D) dosimetry audits. Thus, although the discussion below is mainly based on TLDs, this simply reflects the fact that most practical experience of such mailed audits has used TLDs and the audit methodologies described in this publication were mainly designed using them. Note that various other national systems use a range of other dosimeters (e.g. RPLDs [66, 90, 91] or alanine dosimetry systems [92–96]) or carry out audits based on visits to centres using ionization chambers (ICs) and other dosimeters.

The IAEA, in collaboration with WHO, was the first organization to initiate routine TLD audits on an international scale [38, 66, 68–70]. Since 1969, it has undertaken postal TLD audits to verify the calibration of radiotherapy beams in low and middle income countries, and it has a very well-established system for checking dose in reference conditions. Detailed follow-up procedures for poor TLD results have been implemented since 1996. A second TLD check is offered. If observed discrepancies are still present and cannot be resolved by the local institution or national experts, then on-site visits are offered by the IAEA to help to identify and rectify any remaining problems. Over 50 years, the IAEA/WHO dosimetry audit service has provided more than 17 000 audits to verify the calibration of radiotherapy beams at

more than 2300 hospitals worldwide. On average, 86% of audit results were within the 5% acceptance limit between 1969 and 2018, but IAEA records show a systematic increase in acceptable results, from approximately 50% in the first years of the audit programme to 65−70% in the early 1990s and 97% from 2016 to 2018. After the follow-up of discrepancies, the fraction of acceptable results increased further to approximately 99% in 2018. From 1998 to 2018, around 84% of hospitals that received IAEA dosimeters for the first time had results within the acceptance limits of ±5% between the measured and stated doses for measurements in reference conditions, while around 95% of users that had benefited from a previous dose audit were successful [68].

The Equal-Estro audit system for radiotherapy dosimetry was established in 1991 to cover European centres and uses mailed TLD. It was originally developed as an ESTRO initiative and project, but later transferred out to a separate commercial activity. In addition to audits of beam calibration in reference conditions, the audits were extended in scope to offer checks of a range of other dosimetric parameters in more complex non-reference conditions for both megavoltage photon and electron beams, including phantom developments for the verification of treatment planning systems (TPSs) [73, 97]. This project has audited on average more than 300 beams per year and has checked a significant proportion of the beams in the countries utilizing the service, mainly in the European Union and neighbouring states. The results have shown that 99% of the beam dose calibrations in reference conditions were within the tolerance level of ±5% after the TLD audit procedures were completed. However, further checks have been necessary in more than 20% of the centres involved, concerning the other dosimetric parameters audited, because a deviation larger than ±5% was observed in at least one of the non-reference conditions for one of the beams checked [72]. A similar experience of the potential for a greater level of deviations in more complex and non-reference situations has also been reported by other audit groups; for example, in the case of the dose audits performed by IROC-H of IMRT, stereotactic body radiation therapy (SBRT) and stereotactic radiosurgery (SRS) treatments using ‘end-to-end’ QA phantoms [41, 98–100]. Current data indicate that, on average, 15% of centres cannot successfully meet the acceptance criteria for all parameters tested [40, 41, 73, 78, 79, 94, 99, 101]. This growing experience underlined the need for the IAEA to consider ways to extend regular audits beyond the checks of beam calibration in reference conditions only (i.e. to other parameters in non-reference conditions and to other beam modalities, including the increasing use of advanced technologies) in order to support radiotherapy services in Member States more widely. One cost effective way to do this is to build on the experience of existing national audit systems and also on the experience of the IAEA of working with some countries to develop national networks that can carry out their own mailed TLD audit checks. This approach also recognizes that requirements may be different in different Member States and enables flexibility in the choice of levels of audit to reflect different national priorities.

It may be noted that the existing national and international audit network systems have closely collaborated at various stages, including by exchanging dosimeters and by carrying out cross-measurements, to link and compare their performance and results to ensure that there is a close correspondence in outcome and that they are working to the same minimum levels and standards. Currently such collaboration is regularly carried out between the IAEA system and the main national and international networks. Together with the international network of dosimetry standards laboratories, the Primary Standards Dosimetry Laboratories (PSDLs) and Secondary Standards Dosimetry Laboratories (SSDLs), which is also supported by the IAEA, is a powerful tool in ensuring consistency of quality in dosimetry as used and as delivered in radiotherapy centres worldwide. There is ongoing discussion at the IAEA and at other international organizations, such as the Global Harmonization Group for Radiotherapy QA, concerning the optimum ways to harmonize standards and recommendations for radiotherapy dosimetry audits. This is particularly focused on clinical trials but would also have a direct effect on standard practices for more general audits and would take into account the need for flexibility and the differences in requirements of the different Member States in this field [56, 102, 103].

1.7. EXTENSION OF THE SCOPE OF RADIOTHERAPY DOSIMETRY AUDIT WITHIN THE IAEA FRAMEWORK

To most cost effectively use resources for audit activity and to extend the availability of radiotherapy dosimetry audit to as many hospitals as possible throughout the world, the IAEA has supported the development of methodology and the establishment of national activities in countries where existing resources allow the set-up of national TLD-based QA audit networks for radiotherapy dosimetry (or potentially also systems based on other dosimeters). Thus, a Coordinated Research Project (CRP), titled Development of a Quality Assurance Programme for Radiation Therapy Dosimetry in Developing Countries, was initiated in 1995 and ran from 1996 to 2001 with the aim of assisting IAEA Member States to develop such national programmes, initially for beam calibration audits in reference conditions. The aim of that CRP was to disseminate a uniform TLD methodology for radiotherapy dosimetry audit to the countries involved. In addition, it provided guidelines for the structure and operation of national QA networks in participating countries [104] to give a model that other countries could use. The terminology adopted in the first CRP to describe the national QA network was the External Audit Group (EAG). It may be noted that other names have been recently introduced (e.g. National Radiotherapy Dosimetry Audit Network or simply Dosimetry Audit Network (DAN)). In the following sections DAN will be further used as the preferred terminology. The work of the first CRP was subsequently further extended in methodology and testing in three additional CRPs. These were titled, respectively, Development of a TLD-based Quality Audit Programme for Radiotherapy Dosimetry in Non-reference Conditions, Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques and Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery. The results, experience and outcomes of these CRPs are summarized in this publication. This has been requested by relevant professional and clinical groups in Member States to bring together and make available in one consistent and comprehensive publication all the necessary information required for the development, methodology, implementation and operation of a radiotherapy audit by DANs and information and experiences regarding different developing levels of audit from the DANs.

The overall radiotherapy dosimetry audit approach established and developed throughout this work is one that is based on a process of increasingly complex steps and parameters being checked. An audited centre has to successfully complete the lower level audits before moving on to the higher level audits. This approach was developed so that there would be a clear rationale, relevant to radiotherapy accuracy, quality and safety, for the use of resources and effort, and also so that the experience of previous levels could be used to inform the development, implementation and analysis of results for subsequent levels. Within this hierarchy more complex parameters can be addressed as the audits evolve, and there are some options and decisions at various stages to allow national DANs to choose specific routes and audits and enable the flexibility for national priorities to be taken into account.

This publication mainly discusses audit methodologies using a TLD as the selected dosimeter for point dose measurements, because it is the most widely used system and has been the system used by the IAEA Dosimetry Laboratory and the involved DANs throughout the CRPs [65, 104–106]. However, as noted above (Section 1.6), a range of other dosimetry methods are being investigated or used by national and international audit systems [68, 77, 89–96]. Thus, the methodology here is not intended to exclusively endorse TLD use, but simply reports the CRP experience using TLD as a model. If other measurement systems were to be used by a national audit group, the methodology would need to be suitably modified and tested along similar lines to those reported here.

1.8. SCOPE OF THE PUBLICATION

This publication provides all the information, resulting from the work of four completed CRPs, that is needed by national groups intending to set up, develop and establish a national network for radiotherapy dosimetry audit based on mailed TLD methods for point dose audit measurements, and then develop into

2-D audits (also with applications to 3-D), based on methods using mailed radiochromic film and small solid phantoms. It covers the following types of audits:

(a) A range of radiotherapy beam dosimetric parameters in reference and non-reference conditions for megavoltage radiotherapy photon beams, both on- and off-axis;
(b) Electron treatment beams, on-axis;
(c) Photon beams shaped with multileaf collimators (MLCs);
(d) Photon beams in the presence of heterogeneities to test the performance of TPSs for lung and bone corrections and their local implementation into clinical practice;
(e) Small field 2-D dose distributions, as a precursor to modelling for IMRT;
(f) Photon beam small field output factors shaped with an MLC;
(g) MLC performance for IMRT dose delivery, carried out with film;
(h) Photon beam static gantry single IMRT field (TLD and film);
(i) Photon beam 'end-to-end' IMRT treatment delivery (TLD and film).

It provides information and detail on the following:

(a) The structure and interlinkage of the CRPs in these areas.
(b) Guidelines for establishing national DANs for radiotherapy dosimetry.
(c) The development of the methodology for the suggested TLD audits and the setting up of methods for the suggested 2-D radiochromic film audits.
(d) Results and experience from methodology testing and national implementation of the suggested audits within each DAN involved in the conduct of the CRPs. This provides practical experience that can be used by others for DAN establishment for these audits and for any subsequent more complex or advanced dosimetry audits.
    — Examples of the radiotherapy infrastructure questionnaire, instruction sheets, data sheets and results reporting forms that were prepared for the various audit steps to specify the irradiation conditions and to collect the information necessary for dosimeter evaluation and data analysis, as well as practical instructions for DANs, can be found in the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).
    — It may be noted that there is some overlap between the sections of this report, but this results from specific sections summarizing different areas of work from different CRPs or points in time. In addition, it is recognized that there may be a need in some circumstances for a section to be read as a stand-alone item, and hence for it to contain all the necessary information to support the rest of its content.

2. OVERVIEW OF COORDINATED RESEARCH PROJECTS ON DOSIMETRY AUDIT IN RADIOTHERAPY

2.1. OVERVIEW OF THE FRAMEWORK OF THE DEVELOPMENT OF THE AUDITS

Over two and a half decades, the IAEA has encouraged and supported the development and operation of national activities for QA in radiotherapy. One of the IAEA's main objectives during this time has been to ensure that TLD audits are made available to the largest possible number of hospitals in low and

middle income countries. As experience of radiotherapy dosimetry audits accumulated, and also on the basis of the results and observations drawn from audits in some high income countries and the demands of Member States, it was recognized that an additional objective had arisen — audit methodology and scope had to evolve and develop further. This was needed primarily to cope with more complex radiotherapy situations, and also to deal with radiotherapy equipment performance and TPS modelling for complex and advanced technologies.

CRP E2.40.07, entitled Development of a Quality Assurance Programme for Radiation Therapy Dosimetry in Developing Countries was initiated in 1995. It had the aim of transferring know-how on TLD postal audits of radiotherapy doses in reference conditions for radiotherapy hospitals from the long standing IAEA experience to the national level. Twelve Member States participated in the project: Algeria, Argentina, China, Colombia, Cuba, the Czech Republic, India, Israel, Malaysia, the Philippines, Poland and Viet Nam. The CRP developed a standardized methodology for measurements, which was the same for all participating countries. It provided a framework for setting up a national structure within which to develop and manage radiotherapy dosimetry audits and other linked QA activities and provided a structure for technical backup to the national DAN work. Within this CRP, the Guidelines for the Preparation of a Quality Manual for External Audit Groups on Dosimetry in Radiotherapy were developed and disseminated through the IAEA/WHO SSDL Newsletter to get the information out to potential users at the earliest opportunity [104].

This initial CRP was focused on the most basic level of radiotherapy dosimetry audit (i.e. the beam output check in reference conditions) [69, 70]. The basis for the measurements retained the IAEA audit philosophy of using the most cost effective method of carrying out an external audit for large numbers of radiotherapy centres and for large geographic areas (i.e. using mailed TLDs) and also used the detailed experience built up by the IAEA in these methods. This cost effective approach was extended within the adopted structure of developing and supporting national DANs. The countries set up their TLD systems with technical support from the IAEA Dosimetry Laboratory, which provided an external quality control of the performance of their national TLD systems. Then, initial pilot TLD runs were conducted at the national level with a selected number of hospitals to test methods, instructions, data sheets, etc.; later, the regular audit programme was implemented such that it was extended to all hospitals in each country. In addition to other developments, the TLD standard operating procedures of the IAEA Dosimetry Laboratory were distributed as an example of the approach expected to audit measurements. After the completion of the CRP in 2001, the practical TLD audit methodology developed and tested in the CRP and also guidance on the model for national DAN structure was made available to other countries wishing to establish national TLD audits [104].

Following the end of this CRP, the IAEA continued to support the national DANs from 2001 to 2006 by conducting a second research project: CRP E2.40.12, Development of TLD-Based Quality Audits for Radiotherapy Dosimetry in Non-reference Conditions. This developed from the work of the earlier CRP, which had been concerned only with beam output checks in reference conditions and also from the clear evidence available from other audit systems in a few high income countries that it was necessary to check other additional parameters to further improve the quality of radiotherapy in participating centres [71–74, 83, 107]. The objective of this CRP was then to extend the scope of activities of the national audit programmes from the basic TLD check of the beam output in reference conditions to more complex audit measurements in a variety of clinically relevant irradiation geometries (i.e. in non-reference conditions) and also to provide the initial basis for auditing other radiotherapy modality beams, (electron beams) [108]. The aims included assisting the national DANs in developing a systematic approach for these audits, with a structured programme gradually increasing the complexity of the dosimetry parameters audited. It was intended to address the specific needs of individual participating countries, in order to provide models and experience for a range of different national situations that would be useful for others. Foreseeable factors in this context include differences in already established infrastructure, different histories in previous audit activities, new developments such as new methodology for the various levels of auditing programme, etc. The participants in the second CRP were the national DANs of Algeria, Argentina, Bulgaria, Cuba, China, India and Poland. A three-step flexible mailed TLD audit system (steps 1–3) was developed for national

TLD networks to allow the experience gained from each audit step to be incorporated into subsequent audit steps, and to ensure that more basic levels were audited successfully before more complex steps were included [106].

A further development was then supported within the IAEA framework, as a result of which the third CRP (CRP E2.40.16) was initiated in 2008 and ran from 2009 to 2011, reporting in 2012, as a logical extension of the audit steps previously developed and tested. Its objective was the Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques, and to this end it developed and tested another three steps of radiotherapy dosimetry audit (steps 4–6) to cover the initial essential stages for such treatments [58]. The national DANs participating in this CRP were those of Algeria, Argentina, Brazil, China, the Czech Republic and Poland.

The final CRP (CRP E2.40.18), was initiated in 2012 and ran from 2013 to 2017, as a further extension to more complex audit steps [65, 105]. Its objective was the Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery, and to this end it developed and tested another three steps of radiotherapy dosimetry audit (steps 7–9) to cover the initial essential stages for such advanced treatments. The national DANs participating in this CRP were those of Algeria, Brazil, China, the Czech Republic, India, Poland and Thailand.

The development follows the overall philosophy of the IAEA audit programme of step-by-step progression of audits for increasing layers of complexity of radiotherapy dosimetry. Each step considers critical and significant clinical radiotherapy dosimetry parameters and builds on the experience of the last step. In each case the approach ensures that more basic levels are audited successfully before more complex levels are included. The following nine fully developed and tested steps from the completed CRPs give a clear outline of the overall programme thus far [80]:

> "Step 1: postal dose audits for photon beams in reference conditions, as recommended by TRS-398 [109]. It is necessary for any of the audit systems to successfully implement this step before beginning any subsequent audit step;
>
> Step 2: postal dose audits for photon beams (step 2a) in non-reference conditions on the beam axis and electron beams (step 2b) in reference and in non-reference conditions, on the beam axis. This includes checks of dose variation with field size and shape, wedge transmission for photon beams, and checks of electron beam output, as well as dose variation with field size and treatment distance for electron beams;
>
> Step 3: postal dose audits for photon beams in reference conditions and in non-reference conditions off-axis. This includes checks on selected points in beam profiles, with and without wedges, for both symmetric (Part 1) and asymmetric (Part 2) fields in these beams;
>
> Step 4: postal dose audits for photon beams shaped with multi-leaf collimators (MLC). This includes checks on beam axis of dose variation with field size and shape for a range of MLC shaped regular and irregular fields, including wedged fields. It includes audit of the hospital method to calculate these dosimetric parameters, expecting this to be done with the local treatment planning system (TPS);
>
> Step 5: postal dose audits for photon beams in the presence of heterogeneities. This includes checks in solid phantoms of doses both on and off the beam axis and both inside and beyond heterogeneities, to test TPS and local implementation of approaches for dosimetry modelling and calculation of corrections for the presence of lung and bone in treatment beams;
>
> Step 6: postal dose audits of 2-dimensional small field distributions. This includes checks of dose profiles, particularly penumbra, using radiochromic film in solid phantoms to test the local TPS modelling for small fields as a necessary parameter for accurate modelling for IMRT;

Step 7: postal dose audits for dose rate dependence of small fields shaped with an MLC (step 7a) and a film audit of MLC performance for IMRT dose delivery (step 7b). This includes checks of small field dose rates using published reference data compared to TPS dose calculations and to verify the positioning accuracy of MLC leaves using film as a necessary QA test for IMRT delivery;

Step 8: postal dose audits of 2-dimensional relative dosimetry of a photon beam single IMRT field. This includes a film measurement of a single field IMRT fluence pattern compared to the TPS dose calculations as a necessary parameter for accurate QA of IMRT delivery;

Step 9: postal dose audits of an 'end-to-end' dosimetric quality for IMRT including imaging, treatment planning and delivery. This included the use of a solid phantom containing an imageable target and organ at risk whose TLD and radiochromic film measured doses are compared against the TPS dose calculations as a necessary verification of accurate IMRT delivery."

2.2. OVERVIEW OF THE PROCESS FOR THE DEVELOPMENT OF AUDITS

2.2.1. Background

Developmental work within the four CRPs was structured in a similar way for each of the nine steps of the dosimetry audits from reference conditions to non-reference conditions, to complex techniques and finally to advanced technologies. This section outlines a generic model of the approach to and process of developing new audit methodologies.

2.2.2. Process for audit development

The developmental work carried out in each audit step included two parts: (i) research related to the physical characteristics of the dose measuring systems, phantoms and methods relevant for the specific step and their feasibility for measuring new dosimetry parameters with these devices; and (ii) development and testing of various methodological and operational aspects within the national DANs for hospitals to include these additional steps.

In the first part, for example, scientific investigations of the TLD system parameters were conducted by all countries and the necessary relevant correction factors derived as appropriate [87, 106]. At least some of these are potentially different for different countries, as they may depend on the specific TLD powder material and readout equipment used, and also on other factors involved in the measurement procedures. For dose profile and 2-D dose measurements, film dosimetry had also to be developed and incorporated into the appropriate audit step. Radiochromic film [110–116] was selected due to factors such as physical characteristics, availability of the system in the market, relative costs for the system, ease of mailing and availability already in some DANs. Specifically, for steps 5–9 solid phantoms were necessary to perform the required measurements under varying conditions. The specific phantom design and methods necessitated that the systems be mailable, cost effective and as widely available as possible. For a specific audit step, consideration was given to using existing standard IAEA equipment, but if necessary, new devices such as heterogeneous slab phantoms (step 6) or 'end-to-end' IMRT slab QA phantoms (step 9) were developed as audit tools for specific audit steps.

As a second phase, the auditing procedures and technical documents, such as instructions, forms and data sheets, were developed and adapted to national conditions in each participating country. Before beginning on hospital dosimetry audits at a national or subnational scale, DANs were requested to conduct feasibility studies and pilot tests with only a small number of hospitals, to ensure that any problems in methodology, approach or documentation could be identified and rectified before wider audits were started. Feasibility studies involved self-tests, the exchange of dosimeters with the IAEA Dosimetry Laboratory and potentially other DANs for the purpose of comparison and to ensure that the uncertainties

in the measurement were within the acceptable levels and that all DANs were implementing these approaches consistently. In order to test the practical operation of TLD audits, the technical documents (e.g. application forms, instructions, data sheets) were used in pilot hospital runs. The feedback of the hospitals involved in these pilot runs was used for the improvement of the clarity of the instructions and data sheets. At the same time, the DANs received information on the level of difficulty and time required for a clinical physicist to perform the relevant dose calculations and phantom irradiations on a radiotherapy machine. This pilot exercise was also used to assess the time needed for evaluation of the hospital irradiated dosimeters by the audit measurement laboratories for the various measurement systems and their levels of automation. Where a large number of beams and/or dose points were to be verified, the increased workload involved in reading and evaluating the required number of dosimeters needed to be properly planned for. The national DANs also adapted the common methodology to their local circumstances, taking into account the characteristics of the most commonly used radiotherapy equipment and typical treatment protocols for cancer patients in their countries. This has led to new developments at national levels and provided models and experience for other countries wishing to follow this approach.

The research outputs from these CRPs were as follows:

(a) Specific sets of written guidelines on performing the quality audits for each of steps 1–9, along with guidelines on the evaluation of these audits for radiation dosimetry in the range of defined conditions for each step, were developed and adapted to the local circumstances of each CRP participating country;
(b) A set of extensively tested quality audit dosimeter holders/phantoms for the irradiations defined in each step, capable of assessing an institution's radiation dosimetry practices and performance in the range of defined conditions for each step, was made available for the participants to use;
(c) New methodologies and procedures for new modalities or treatment techniques to be audited using TLD and/or film dosimeters were developed;
(d) Expertise and technology developed under these CRPs were validated by the national organizations or networks and are available for transfer to other countries [80].

The research outputs from these CRPs contribute to the overall increase in experience and expertise in these areas of radiation dosimetry. They also contribute to improving quality and to reducing the number of potential mis-administrations of the dose to radiotherapy patients. Hence, better cooperation and standardization of radiation dosimetry practices is expected at the national level (and potentially the international level) for those countries participating in the CRPs. Further, the availability of these results to any other country as models and examples [80] means they have the potential to provide the same effects and improvements for radiotherapy dosimetry in other countries that were not involved in the CRPs.

The next sections describe the development of a DAN and the methodology details and results associated with each of the audit steps 1–9, as developed within the four CRPs. In addition, for completeness, some associated secondary analysis derived from the development and testing of each CRP audit and from linked IAEA projects associated with these CRPs is included. The data below may be used as a cohesive and comprehensive set of guidance and reference material for any country wishing to establish similar audit systems for radiotherapy dosimetry, up to and including the steps suggested and tested, after which it can be used as a model for subsequent developments.

3. GUIDELINES FOR ESTABLISHING A NATIONAL DOSIMETRY AUDIT NETWORK FOR RADIOTHERAPY

This section comprises the overview of Setting up a Dosimetry Audit Centre: Infrastructure and Resources, SSDL Newsletter No. 66 [117], which reports the recommendations of a group of international experts on setting up a dosimetry audit centre. Please refer to the original publication for the details.

3.1. INTRODUCTION

It is estimated that, at most, only two thirds of RT centres worldwide take part in external quality audits [63, 118]. It means that there is a possibility that some centres not participating in audits deliver suboptimal treatments because of inferior dosimetry causing the difference between the prescribed and delivered doses. Radiotherapy patients risk suffering from consequences of erroneous dose delivery which include the decrease of tumour control probability, increased treatment morbidity and toxicity and impact on the patient's immediate and long-term quality of life and even survival [9]. It is widely recognized [51, 67] that a successful quality assurance programme includes an independent dose check. Regular participation in an ongoing quality audit service provides added assurance that LCs maintain good dosimetry practice. Within the CRPs described in this publication, the administration of the quality audit programme is conducted by a DAN, formerly also termed an EAG.

3.2. AIM OF THE DAN

The DANs are responsible for organizing and performing quality audits for radiotherapy dosimetry in their own countries or regions and have the aim of ensuring high accuracy and precision of dose delivery at appropriate levels of testing. If the need arises and resources allow, a DAN should be willing to provide its services to other radiotherapy centres in countries within the regions that are not currently able to establish a DAN. The activities of each DAN should represent the local situation and use scientifically proven approaches and internationally harmonized measurement and auditing practices. It is essential that DAN obtains the approval and recognition within the local radiotherapy community (e.g. radiation oncology and medical physics societies). It is also important to get the support of national bodies to ensure sustainability of the activities and appropriate allocation of resources.

When each DAN conducts dosimetry audits, it needs to consider the experience of other existing audit networks and make sure that all beam modalities in clinical use are audited in each radiotherapy department at least at the level of reference conditions. Frequencies of audits need to be discussed and agreed, and discrepancies identified should be followed up. It is strongly advised that all new radiotherapy treatment machines/modalities be audited before the first patient treatment [9, 53]. Audits also need to be performed after repairs of treatment units and after replacements of radioactive sources. Audits may also be requested when new radiotherapy related systems are installed and before they go clinical (e.g. new TPSs).

3.3. NATIONAL RADIOTHERAPY INFRASTRUCTURE DATABASE

Each DAN needs to create a national database on RT infrastructure that includes information on staffing, radiotherapy equipment and QA procedures. An example of the type of infrastructure questionnaire that may be used as a starting point for developing a database (Package 1) is a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

The DAN has to ensure that the infrastructure database is continuously updated, meaning that the DAN administration remains in regular contact with each centre. One way to achieve this, for example, is to organize regular national meetings to discuss topics such as infrastructure, audit progress, audit results, new audit developments and priorities.

3.4. STRUCTURE OF THE DAN

A DAN (alternatively known as an EAG) includes a dosimetry audit centre (DAC) and other components: participating hospitals, a clinical medical physics group (MPG), a measuring centre (MC) and the standards dosimetry laboratory (usually an SSDL or, in some instances, a PSDL). Depending on the location of the DAC, either within a SSDL or independently, DAN can be structured in one of the two ways as shown in Fig. 1 (reproduced from Ref. [117]). It is important that DAN operation is maintained according to international standards [119]. Regardless of the DAC structure within a DAN, a DAC needs to have connections to radiation oncologists, other DACs and LCs. Detailed descriptions of the DAN components, roles and responsibilities of staff and level of their qualification are given in Setting up a Dosimetry Audit Centre: Infrastructure and Resources, SSDL Newsletter No. 66 [117].

3.5. DAC DEVELOPMENT AND OPERATIONS

An example of tasks to be performed during different DAC development and operational stages, together with the relative effort needed by DAC staff, is shown in Table 1 [117]. Detailed descriptions of the tasks and steps are given in Setting up a Dosimetry Audit Centre: Infrastructure and Resources, SSDL Newsletter No. 66 [117].

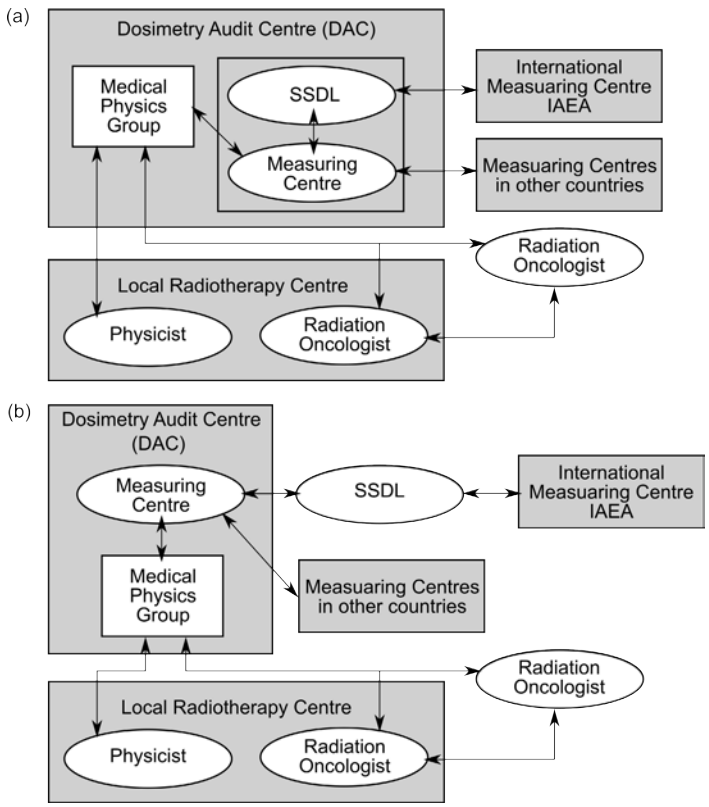


FIG. 1. The two most common DAN structures (reproduced from Ref. [117]).

TABLE 1. NECESSARY TASKS FOR ESTABLISHING AND MAINTAINING A DAC: STARTUP (S), DEVELOPMENT (D) AND DAILY OPERATIONAL (O) PHASES
(*reproduced from Ref. [117]*)

Tasks	Startup	Steps 1 and 2b		Steps 2 and 3		Steps 4–6		Steps 7–9	
	S	D	O	D	O	D	O	D	O
Recruitment	√√√	√	√	√	√	√	√	-	-
Audit development	√√	√√√	√	√	√√	√	√√	-	√
Audit ongoing improvement	-	√√	√	√	√	√	√	-	-
Training	√	√√	√	√	√	√	√	-	√
Administrative tasks	√√	√	√	√	√	√	√	√	√
Logistics	√√√	√	-	√	-	√	-	-	√
Equipment purchase and commissioning	√√	√√√	-	√	√√	√	√√	-	-
Audit implementation	-	√√√	√√	√	√√	√	√√	-	√
Audit follow-up	-	√	√√	√	√√	√	√√	-	-

Note: Startup: Development of DAC infrastructure.
Steps 1 and 2b: Audit of photon and electron beam outputs in reference conditions.
Steps 2 and 3: Audit of photon and electron beam parameters in non-reference conditions.
Steps 4–6: Audit of beam parameters for complex treatment modalities.
Steps 7–9: 'End-to-end' audit for advanced dose delivery techniques.

3.6. DAC AUDITS AND REQUIRED RESOURCES

All of the audit steps (steps 1–9) developed in the four CRPs are remote audits. At the same time, the DAC may choose to opt for on-site approach with auditors (travelling to hospitals personally) or use both methods.

This section identifies a minimum of one audit step with the startup phase and potentially up to a total of nine audit steps of increased complexity in addition to the startup phase that a DAC can implement within the DAN. Section 4 of this report gives examples of audit step implementation using TLD and film dosimeters. However, a DAN may choose to use different dosimeters, adapting the methodology. The implementation of any of the audit steps and using the different potential dosimetry resources shown in Table 2. Detailed descriptions of the auditing approaches and dosimetry systems used depending on the complexity of the audits provided are given in Ref. [117].

TABLE 2. POTENTIAL DOSIMETRY EQUIPMENT FOR EACH AUDIT LEVEL FOR REMOTE (R) AND ON-SITE (O) AUDITS
(*reproduced from Ref. [117]*)

Applicable dosimetry equipment	Steps 1 and 2b Reference conditions		Steps 2 and 3 Non-reference conditions		Steps 4–6 Complex		Steps 7–9 Advanced	
	R	O	R	O	R	O	R	O
Dosimeters[a]								
TLD[b]	√	√	√	√	√	√	√	√
OSLD[c]	√	√	√	√	√	√	√	√
RPLD[d]	√	√	√	√	√	√	√	√
Alanine	√	√	√	√	√	√	√	√
IC[e]	√	√	√	√	√	√	√	√
Film			√	√	√	√	√	√
Diode			√	√	√	√	√	√
2-D array				√	√	√		√
3-D array				√	√	√		√
3-D dosim. (gel)							√	√
Phantoms								
Water	√	√	√	√	√	√		
Geometric/solid	√	√	√	√	√	√		
Semi-anthropomorphic or anthropomorphic					√	√	√	√

[a] Require appropriate dosimeter readout device.
[b] TLD: thermoluminescent dosimeter.
[c] OSLD: optically stimulated luminescence dosimeter.
[d] RPLD: radiophotoluminescence (glass) dosimeter.
[e] IC: ionization chamber.

3.7. SUMMARY

This section provides a short overview of the infrastructure, equipment and resources needed to establish a DAN and its DAC. It is emphasized that a successful operation of a DAN requires strong support from the professional community, national authorities and government bodies. It is also important to secure appropriate funding to ensure sustainability of audit services. Technical and professional capacity of the established DAC is of vital importance, staff should include expert medical physicists

which should be additionally appropriately trained to operate specific equipment and have necessary soft skills to efficiently interact with audit participants.

Truly successful DAC has continuous support from its customers and is driven by the community demand to continuously improve the quality of its services and complexity of its audit methodologies for the benefit of patients receiving accurate and safe radiotherapy treatments. Independent from the audit type provided (on-site or remote, or both), DAC services should be based on internationally recognized standards and codes of practice [109, 119–121]. An important role of DAC is to assist LCs in implementing new technologies, and it requires staff specific knowledge and sufficient clinical experience, familiarity with important measurement and auditing approaches described in relevant publications [122–130].

4. AUDIT STEPS — METHODOLOGY AND TESTING

4.1. STEP 1: TLD AUDITS FOR PHOTON BEAMS IN REFERENCE CONDITIONS

4.1.1. Introduction to the step 1 audit

The aim of the step 1 audit was to verify the beam output in reference conditions for photon beams using TLDs. The methodology and testing of this step at the national level was completed in the first CRP in this series, E2.40.07 [66, 131]. This CRP, Development of a Quality Assurance Programme for Radiation Therapy Dosimetry in Developing Countries, ran from 1995 to 2001 and involved 12 Member States (Algeria, Argentina, China, Colombia, Cuba, the Czech Republic, India, Israel, Malaysia, Philippines, Poland and Viet Nam). The main goal of this first QA programme CRP was to transfer knowledge and experience of TLD-based postal/remote audits of radiotherapy [69, 70] doses in reference conditions for radiotherapy hospitals from the long standing IAEA experience to the national level. The aims to achieve the CRP's goal included supporting the development of national audit programmes, providing a framework for setting up national approaches for this development, disseminating a uniform TLD methodology for radiotherapy dosimetry audit to those national programmes, providing guidelines for the structure and operation of national QA networks [104] and providing a model that other countries could implement on a national scale. The concept of an EAG, referred to as a DAN in this report, was introduced and developed at this time.

There was a clear recommendation from the IAEA that it is necessary for any country first entering the proposed audit process to successfully implement this step 1 audit before considering the subsequent audit steps. It is advised that step 1 be carried out in all hospitals and for all photon beams, even where the hospital has more than one beam of the same quality. It was furthermore later proposed that all audit measurements in reference conditions be performed at a depth of 10 cm in water, in accordance with the recommendations in TRS-398 [109].

4.1.2. Methodology of the step 1 audit

The step 1 audit retained the well-established IAEA audit approach and experience of using mailed TLDs and the simple IAEA standard holder for reference beam output verification of photon beams (Fig. 2 reproduced from Ref. [106]). This holder is lightweight (for mailing), simple to assemble and easy to set up in a simple water tank.

This standard holder for photon beams has been extensively described and has been in use for a long period of time in slightly different forms [39, 69, 70, 73, 87, 132]. It is now standardized to only have a single hole to hold a TLD capsule at 10 cm down the vertical tube (Fig. 2), such that TLDs will be placed at 10 cm depth in water when the water surface is aligned with the top of the tube, in keeping with the IAEA's TRS-398 dosimetry protocol approach of reference depths for all high energy photon beams of

FIG. 2. Standard TLD holder for dosimetry audits of photon beams (reproduced from Ref. [106]).

10 cm [109]. The holder also has a lead ring placed at the bottom to add weight for the stability of the holder when placed in a water phantom.

For pilot or full national studies involving hospitals in the countries of each DAN, TLDs are sent to the hospitals by the DAN, with the standard IAEA holders and instructions and data sheets for ^{60}Co and high energy X ray beams. Hospitals are requested to irradiate the TLDs in a water phantom in reference conditions as defined by TRS-398 [109]. The dose delivered to the TLDs is calculated using routine clinical data, in the same manner as would be performed for patient treatments.

Once the irradiated TLDs arrive at the DAN dosimetry laboratory, the thermoluminescent signal is measured following the methodology and correction factors outlined in Appendix I and the doses are evaluated for each dosimeter set. The results are reported to participants in the form of the relative deviation of the evaluated dose to the participant's stated dose or the ratio of these doses. The acceptance limit of ±5% typically applied defines the maximum discrepancy between stated and measured doses, and all results outside this limit are followed up. It is usually done using repeated TLD irradiation and investigation of the reasons for the discrepancy. If the deviations persist, an expert visit should be conducted. Immediate action is necessary if a deviation greater than ±10% is found. Some DANs utilize more detailed deviation categories, for example, an optimum level of 3.0% to 3.5%, which corresponds to the expanded standard uncertainty (k = 2) of their TLD systems.

4.1.3. Development and testing of the step 1 audit methodology

For each country and DAN that has set up its own TLD system, this was done with technical support from the IAEA Dosimetry Laboratory, which provided external quality control of the performance of their national TLD systems. Initial pilot TLD runs were conducted between national systems and the IAEA laboratory, and then at the national level with a selected number of hospitals to test methods, instructions,

data sheets, etc. As part of this pilot run, TLD system characterization, various correction factors including holder corrections, and related uncertainties, were determined by each national group for comparison and analysis using the IAEA Dosimetry Laboratory TLD standard operating procedures as a starting point. This resulted in guidance on practical TLD-based audit methodology and recommendations to achieve high measurement accuracy. This experience was summarized in, and incorporated into, the TLD system description, characterization and methodology guidelines produced at the end of the first CRP [104, 133]. The TLD guidance was later updated, and this is reproduced in the current report as Appendix I, so this feasibility and development work is not discussed further in this section. In addition, the step 1 audit methodology was modified over time. A number of publications present aspects of this work, including information on various corrections and uncertainties of the system [38, 66, 69, 70, 87, 88, 104, 132, 133].

The step 1 audit has been implemented extensively over the past five decades. A number of publications present distributions of IAEA or DAN audit-measured dose versus hospital-stated dose in reference conditions, across ranges of hospitals and at different times [38, 66, 69, 70, 82, 107, 131, 132]. In addition, as a part of these QA programme CRPs, specific reference irradiations are provided by the IAEA Dosimetry Laboratory for external quality control of DAN TLD systems. DANs are invited to send their dosimeters to the IAEA annually for reference irradiation which includes irradiation with unknown to the DAN dose, so-called 'blind check'. The results of 15 years (2004–2018) of these reference quality control irradiations are presented in Fig. 3.

The results from 26 DANs as shown in Fig. 3 indicate a mean of the $D_{(DAN)}/D_{(IAEA)}$ distribution of 0.999, where D represents the dose, and a relative standard deviation (SD) of 1.6%. From these results and subsequent ones, the DANs have demonstrated their consistency and adequate accuracy when reporting doses determined by their dosimetry systems.

4.1.4. Results of the national runs for the step 1 audit

Within each CRP, it was part of the approach for each of the DANs to perform a national run of the implemented audit step. Examples of the results of the national runs for the step 1 audit as conducted in five different countries (Algeria, Argentina, Bulgaria, India and Poland) are presented in Fig. 4.

The results of the step 1 audits for DANs from the five countries (numbers are used for anonymization purposes) were collected during the duration of the CRP. These DANs took advantage of the methodology developed by the IAEA to extend their QA programmes to reach additional radiotherapy

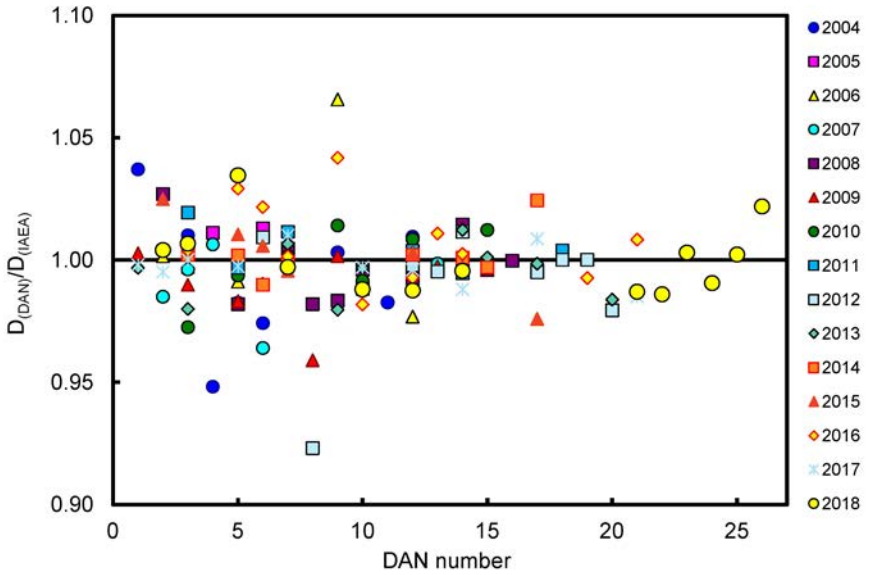


FIG. 3. The results of the DAN 'blind checks' for 2004–2018: DAN versus IAEA reference irradiations.

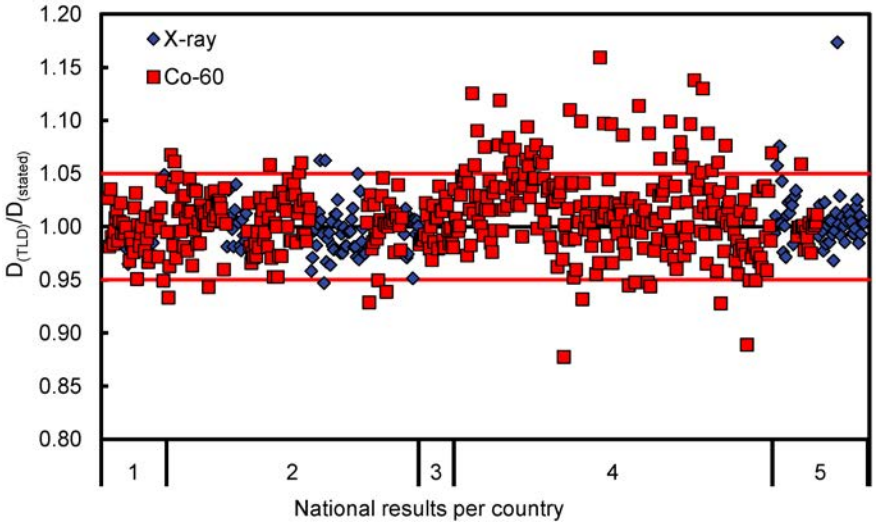


FIG. 4. Results of TLD audits performed in reference conditions for Co-60 beams and high energy photon beams in five countries.

centres to improve the overall treatment of patients. Audits were conducted for both ^{60}Co units and linacs. On average, the results from these audits from the five countries had the mean value of near unity (1.004) with 2.9% SD. The majority of the results for countries 1, 2, 3 and 5 were within the 5% acceptance limit, as shown in Fig. 4. For example, in country 2, around 94% of all results were within the 5% limit.

However, there were occasions when the results achieved by implementing this audit were not as good, as can be seen for country 4 in Fig. 4. Table 3 represents results from a sixth country (not shown in Fig. 4) where, until 2002, only about 80% of the results were within the 5% limits. This larger number of discrepancies resulted in a considerable amount of follow-up and discrepancy resolution effort. They also reinforce the need for this specific audit. In all cases, follow-up resulted in a much higher percentage of results falling within the 5% criterion. If the repeat TLD audit did not resolve the discrepancy, then DAN physicists would make an on-site visit to the centre. These efforts resulted in improved results for the years 2005 and 2006 (i.e. ≥90% of checks were within the ±5% tolerance).

4.1.5. Summary and conclusions for the step 1 audit

In all countries the experience from the step 1 dose audit at the national level (i.e. audit of doses in reference conditions) was positive and useful. Overall, in a large proportion of the hospitals checked, the results showed good agreement between the measured and stated doses within the ±5% limit. A significant number of hospitals that had never participated in an external dose audit before were included in the project. The experience bore out previous evidence [38] that such hospitals typically show a greater proportion of deviations outside the 5% tolerance and some at the major deviation level outside 10%, further underlining the necessity of external audit for high quality radiotherapy dosimetry to be widened out to as many as possible of the hospitals in the world that are providing radiotherapy. For those hospitals where results were outside tolerances, at the minor or major deviation levels, the work of the CRP allowed problems to be identified and rectified, thereby improving radiotherapy dosimetry in those situations and for patients in those centres. After corrections, many of those hospitals were helped to improve their results to within the ±5% limit. Major reasons identified for deviations that occurred over the years included incorrect beam energy used, incorrect calibration depth, calculation errors, not using up-to-date dosimetry protocols, problems with equipment and problems with practical procedures.

Overall, the CRP work on the dose checks of beam calibration in reference conditions has shown the feasibility of the use of the IAEA's expertise in postal TLD audits by national networks. It has provided standardization of methodology between a wide range of national groups for these audits. This gives an

TABLE 3. RESULTS OBTAINED FOR FIRST CHECK TLD AUDITS IN REFERENCE CONDITIONS IN A SIXTH COUNTRY BETWEEN 1997 AND 2006

Year	No. of beams	Results within ±5%	Results outside ±5%	% within tolerance
1997	9	7	2	78
1998	91	72	20	79
1999	61	37	24	61
2000	45	37	8	82
2002	50	40	10	80
2004	51	43	8	84
2005	30	27	3	90
2006	39	36	3	92
1997–2006	377	299	78	79

internationally consistent framework within which to operate these QA procedures, to report and compare results and to ensure a similar basic level of QA in this area to support radiotherapy in different countries.

The instruction sheets, data sheets and results reporting forms that were prepared for audit step 1 to specify the irradiation conditions and collect the necessary irradiation information (Package 2) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.2. STEP 2A: TLD AUDITS FOR PHOTON BEAMS IN NON-REFERENCE CONDITIONS

4.2.1. Introduction to the step 2a audit

Following the closure of the first CRP (E2.40.07) dealing with dosimetry audits, the IAEA continued to support the national DANs from 2001 to 2006 by conducting a second research project: CRP E2.40.12, Development of TLD-Based Quality Audits for Radiotherapy Dosimetry in Non-reference Conditions. This grew naturally from the work of the earlier CRP, which had been concerned only with photon beam output checks in reference conditions and also from the clear evidence available from other audit systems in developed countries that it was necessary to check additional parameters to further improve the quality of radiotherapy in participating centres. The main goal of this second QA programme CRP was to develop methodology for this remote auditing step and to test, verify and establish it at the national level.

The aim of the step 2a audit, TLD audits for photon beams in non-reference conditions, was to audit various radiotherapy dosimetry parameters in non-reference conditions on the beam axis. This included checks of dose variation with field size and shape and also of wedge transmission for photon beams, all at 10 cm depth in water. Because these are referred to audit in reference conditions, the step also includes at the same time a repeated step 1 audit. However, the latter will not be discussed in detail here, as it follows the same approach as is presented in Section 4.1.

It was decided not to include measured checks of beam quality (depth dose), based on the wide experience of other audit systems, which have reported negligible levels of deviations in this parameter, and to help make the measurement set realistically manageable [72, 73, 132]. Instead, it was decided to

request hospitals to provide TPS-calculated values in a range of clinical situations in order to allow the auditors to evaluate the consistency of data in clinical use in the hospital.

The methodology and testing of step 2a at the national level was described in the literature [66, 106] following the completion of the CRP. Algeria, Argentina, Bulgaria, China, Cuba, India and Poland participated in this project.

4.2.2. Methodology of the step 2a audit

If a national DAN had successfully implemented step 1, and if they had chosen to continue with the non-reference photon beam audits as their next priority, then they could proceed to step 2a. This step was intended to be carried out in all hospitals, but only for selected beams (maximum three beams per hospital).

The step 2a audit retained the simple IAEA standard holder, initially developed for reference beam output verification of photon beams, as described in Section 4.1. In keeping with this, all measurements were carried out at 10 cm depth in a water phantom. Holder corrections (to measured TLD doses) are discussed and adopted values reported in Izewska et al. [106].

All measurements in non-reference conditions in step 2a were carried out on the beam central axis and the option was given to carry out the measurements necessary for SSD or source to axis distance (SAD) conditions, as selected by the hospital. TLD irradiations for the non-reference conditions were carried out with the following irradiation set-ups:

(a) Output of beam in reference conditions, as specified in step 1 (Section 4.1): a TLD at 10 cm depth, 10×10 cm^2 field; this measurement was carried out twice;
(b) Variation of output with field size: one TLD at 10 cm depth for each of the following field sizes: 7×7 cm^2, 20×20 cm^2, 7×20 cm^2;
(c) Dose variation with wedges: a hospital could select either the most commonly used wedge or the steepest wedge, or both, as decided locally for the national programme. Then, for each of the wedges used, one TLD was used at 10 cm depth for 10×10 cm^2 and 7×20 cm^2 field sizes. For the 7×20 cm^2 field the short side was in the direction of the slope of the wedge. Each TLD had to be positioned such that its axis was perpendicular to the slope of the wedge. Half of the dose had to be given with the wedge in one orientation and the other half with the wedge in the opposite orientation. If, on a cobalt unit, the wedge did not cover a 20 cm field in the direction perpendicular to the slope of the wedge, then this field dimension was to be set to be the largest covered. The other dimension — in the direction of the slope of the wedge — should still have been 7 cm.

For these audit measurements, TLDs were sent to hospitals by the DAN, with the standard IAEA holders and instructions, and data sheets for ^{60}Co beams and high energy X rays. Hospitals were requested to irradiate the TLDs in a water phantom in the conditions above, as described in greater detail in the instruction sheets. The hospitals were requested to calculate the doses delivered to the TLDs using routine clinical data, in the same manner as would have been performed for patient treatments.

All returned irradiated TLDs were evaluated by the DAN MC, for the absorbed dose to water (in Gy) to the TLDs and for dosimetric parameters derived from the dose measurements (i.e. field size factors as open field parameters and wedge transmission factors as wedge field parameters). The values reported by the participants were compared to the TLD-determined values. The results were prepared in the form of an individual certificate that was returned to each participant together with the summary of all results and were analysed in relation to the predetermined 5% tolerances.

4.2.3. Development and testing of the step 2a audit methodology

Nine countries participated in feasibility work and multicentre pilot test runs between national systems and the IAEA Dosimetry Laboratory [106], including DANs in Algeria, Argentina, Bulgaria, China, Cuba, India and Poland, and radiotherapy hospitals of the research agreement holders in Austria

and the UK. There was also some participation by the Equal-Estro laboratory based in France. Together, these audit developments were tested using 20 high energy photon beams (^{60}Co, 6–23 MV). The purpose was to assess the methodology used for the audit to measure the dosimetric parameters for photon beams in non-reference conditions for this audit step and also to assess the documentation. During this process, any pitfalls of the proposed approach to these quality audits were identified and corrected. The TLDs and holders for this were prepared by the IAEA Dosimetry Laboratory and distributed to participants. The TLDs, when returned, were evaluated and the results reported to the participants by the IAEA Dosimetry Laboratory.

The results achieved in this multicentre pilot study of TLD audits in non-reference conditions on-axis (and with a repeated audit in reference conditions) are shown in Fig. 5. This illustrates the dose ratios of the IAEA TLD-measured dose to the participant-stated dose in reference conditions, non-reference conditions on-axis for open symmetric fields and on-axis for wedged symmetric fields, for the field sizes listed above. Each data point represents the measurement with two TLDs for the reference and one TLD for non-reference conditions. In total, 203 measurement points were taken for ^{60}Co and high energy X ray beams in the range of 6–23 MV. The study overall demonstrated a good outcome between the centres and the IAEA for photon beam doses in non-reference conditions on-axis, with a mean ratio of the measured dose to the participant-stated dose of 0.999 and with an SD of the distribution of 0.013. All measured doses were within the ±5% tolerance. Statistical distributions of the various groups of measurements shown in Fig. 5 have a spread of results, with the SD varying between 0.011 for open fields and 0.015 for wedged fields.

4.2.4. Results of the national runs for the step 2a audit

Within each CRP, it was part of the approach for each of the DANs to perform a national trial run of the implemented audit step. The participating countries had different levels of roll-out for this step. All seven DANs carried out national pilots for step 2a in at least a few hospitals in their country to test applicability in the national situation. Five out of the seven participating countries carried out national runs for step 2a, including either all centres in their country or a significant number of centres, within the timescale of the CRP. Combining the reported results from the participating countries, these included 974 irradiations with 184 beams. In these cases, the TLDs and holders for this were prepared by the DAN's MC and distributed to participants. The TLDs when returned were evaluated and reported to the participants by the DAN, in terms

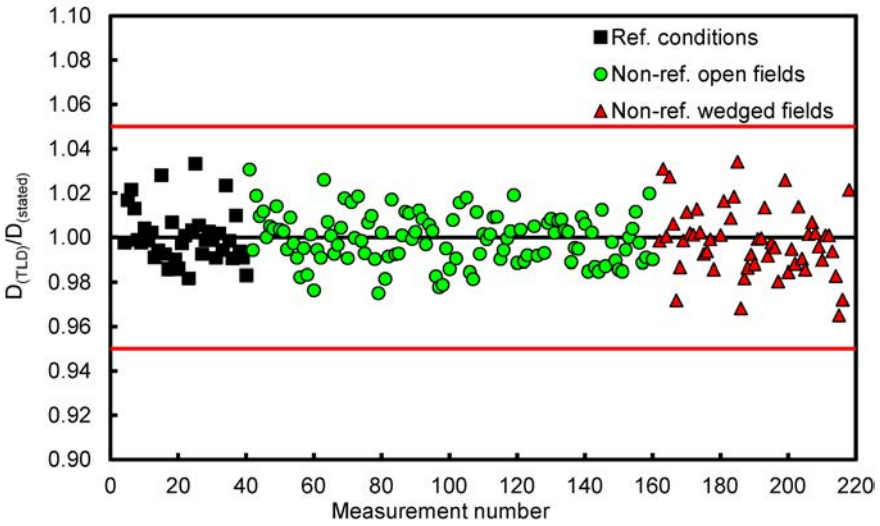


FIG. 5. The results of the multicentre pilot study for non-reference conditions on-axis for symmetric fields and for the associated repeat multicentre audit in reference conditions. The presented data are ratios of the IAEA TLD-measured dose to the participant-stated dose.

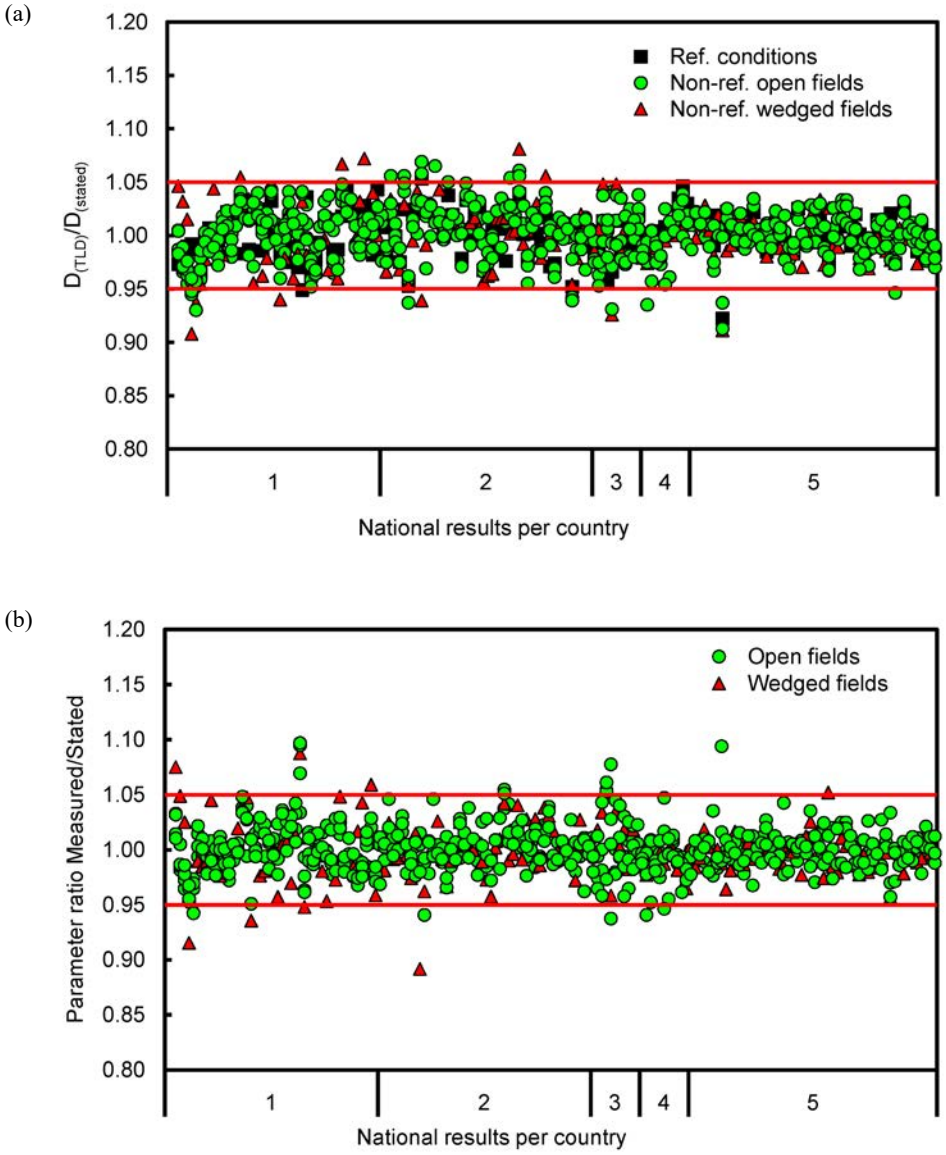


FIG. 6. Results of TLD audits performed in non-reference conditions for high energy photon beams obtained in national runs: (a) dose ratio; (b) parameter ratios.

of DAN measured doses compared to hospital-stated doses and parameter ratios (ratios of measured doses), compared to hospital-stated parameters. A summary of national audit runs for the step 2a audit is presented in Fig. 6 for five countries, for (a) dose ratios and (b) parameter ratios.

Country 1 carried out three runs, including 266 irradiations in 46 separate beams, showing 3/228 open field dose measurements (and 6/38 wedged fields) outside the 5% tolerance. Country 2 carried out two runs (238 irradiations in 48 beams). In reference fields 98% of results were within 5%, while for open fields 92% of dose ratios and 98% of parameter ratios, and for wedge measurements 93%, were within 5%. One measured wedge factor was greater than 10% compared to the stated value. Country 3 included 66 irradiations in 11 beams, showing one wedge dose ratio, five open field parameters and one wedge factor outside 5%. Country 5 carried out two runs, including 278 irradiations in 56 beams. They indicated one beam with systematic deviations, one other dose ratio and one other wedge factor outside 5%.

Several comments were made by DANs on testing the step 2a methodology at the national level. One DAN observed many mistakes in applying the methodology in the early national trial run, and therefore it organized a workshop for participating institutions, after which the compliance and results significantly

improved. Another DAN observed around 20–25% of dose measurements in non-reference conditions out of tolerance (including multiple parameters of one beam, indicating an overall dose calibration issue). The causes were identified and rectified after that audit run, and as a result, at a second run no out of tolerance doses were observed. A third DAN also saw a systematic deviation of one beam in national pilot studies (giving around 15% of individual dose measurements outside 5%) and reported issues with wedge beam audit methodology, requiring further work.

All DANs, other than the third DAN described above, indicated that the audit methodology and documentation were feasible for extending to the national level, and some countries demonstrated clearly that the methods were now adopted as routine in their audit programme. At least one country, as above, reported the value of an educational workshop to explain the audit methods to institutions. Other observations from these exercises include the following:

— Local physics time necessary for irradiation of audit dosimeters and reporting to the data sheets ranged between 4 and 7 hours, depending on experience and local resources. One DAN that uses medical physicists from clinical centres to carry out the DAN work part-time in addition to their normal clinical duties reported that they needed a long period (around one month) to read out the TLDs in the MC for a run of 23 hospitals.
— There was a tendency for more problems with non-reference irradiations compared to reference irradiations, and with wedged field irradiations compared to open field irradiations.
— Problems resulting in measurements or parameters out of tolerance were identified and rectified, some at the 10% level, thereby improving dosimetry in the centres involved and in the country of that DAN. Reasons noted included issues resulting from outdated treatment equipment and dosimetry tools, calibration problems, QA limitations, lack of trained staff, and the need for hospital staff to gain familiarity with the audit methods to be able to implement them accurately.
— Some DANs modified the methodology (e.g. selection of field sizes to suit locally agreed upon requirements).

4.2.5. Summary and conclusions for the step 2a audit

All participating DANs performed a national trial, and most fully implemented the step 2a audit for photon beams in non-reference conditions on-axis to the national level, many doing multiple runs. Overall, the DANs used the developed methodology and documentation in step 2a for photon beams in non-reference conditions on-axis to extend their QA programmes to reach additional radiotherapy centres and/or to include additional audit of dosimetric parameters. In addition, they identified and rectified issues in individual centres, and hence improved the overall dosimetry practices in their country for the radiotherapy treatment of patients. Audits were successfully conducted for both ^{60}Co units and linacs. These audits indicated that the majority of the results for all involved countries were within the 5% acceptance criterion, where typically more than 90% of all results for each dose/parameter grouping were within the 5% tolerance. Means of all distributions were close to unity and SDs of the distributions were typically a little larger than the 2–3% SD observed for photon beams in reference conditions on-axis.

However, there were some groupings where the results achieved by implementing this audit were not as good as seen above, and only 75–85% of results were within the 5% criterion. These resulted in the need for significant follow-up and further work, but also led to improvements in national radiotherapy dosimetry. These findings reinforce the need for this specific audit to ensure that such parameters are included in QA audit programmes and are improved where necessary. In all cases, follow-up resulted in improvement.

Overall, the experience of the audit implementation of step 2a demonstrated that the methods were feasible to extend to the national level within a country's national DAN structure. It has provided standardization of methodology between a wide range of national groups for these audits. This gives an internationally consistent framework within which to operate these QA procedures, to report and compare results and to ensure a similar basic level of QA in this area to support radiotherapy in different countries.

The final detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 2a to specify the irradiation conditions and collect the necessary irradiation information (Package 3) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.3. STEP 2B: TLD AUDITS FOR ELECTRON BEAMS IN REFERENCE AND NON-REFERENCE CONDITIONS ON THE BEAM AXIS

4.3.1. Introduction to the step 2b audit

The step 2b audit was developed and tested within CRP E2.40.12, Development of TLD-Based Quality Audits for Radiotherapy Dosimetry in Non-reference Conditions. One of the objectives of this CRP was to extend the scope of the activities of the national audit programmes from the basic TLD check of photon beam output in reference conditions to providing the initial basis for auditing other radiotherapy modality beams (i.e. electron beams). The participants of the project were the national DANs of Algeria, Argentina, Bulgaria, Cuba, China, India and Poland.

For each country or DAN, respectively, that set up its own TLD system, this was done with technical support from the IAEA Dosimetry Laboratory, which provided external quality control of the performance of national TLD systems. Next, initial trial TLD runs were conducted at the national level with a selected number of hospitals to test methods, instructions, data sheets, etc., after which the regular audit programme was implemented to enable it to be extended to all hospitals in the country.

There was a clear recommendation from the CRP that it is necessary for any country entering the proposed audit process for the first time to successfully implement the step 1 audit before considering the subsequent audit steps. This was particularly true for the implementation of the step 2b audit, which was a natural follow-on from the basic TLD check of photon beam output in reference conditions. It was advised that step 2b be carried out in all hospitals and for two electron beams, a low energy (<10 MeV) beam and a high energy (≥10 MeV) beam.

4.3.2. Methodology of the step 2b audit

The electron TLD holder (Fig. 7) used in the step 2b audit has a weighted base for stability and three vertical tubes. The standard IAEA TLD capsule is located in a TLD shaped slot in the middle of a circular poly(methyl methacrylate) (PMMA) plate, which is positioned onto the three vertical tubes and rests against pins in the tubes. The height of the TLD plate on the tubes, and hence the depth of the TLD below the water surface when the holder is placed in water and the water surface is aligned with the tops of the tubes, is adjustable by using sets of precise spacers beneath the plate and the pins. Hence the TLD can be adjusted precisely for depth in water to match the required depths of dose maximum (z_{max}) for a range of electron beams.

All these step 2b audit checks are carried out with the TLD positioned at the depth of dose maximum for the selected electron beam and field size, using the special TLD holder designed for electron beams. Radiotherapy centres were requested to carry out these checks in two electron beams, one in the energy range of 6–9 MeV and the second in the energy range 10–15 MeV, or as near as possible, depending on the treatment equipment available.

Measurement conditions:

— Dose output: 10 × 10 cm^2; normal SSD; this measurement to be carried out twice;
— Dose variation with field size: 6 × 6 cm^2 or nearest achievable; normal SSD;
— Dose variation with treatment distance: in centres where different SSDs are used for different clinical applications; a supplementary check needs to be performed at one such SSD, with a 10 × 10 cm^2 field size.

FIG. 7. Standard TLD holder for electron beams.

All returned TLDs were evaluated by the DAN MC both for the absorbed dose to water (in Gy) and for dosimetric parameters derived from the dose measurements, such as field size factor and SSD factor. The values reported by participants were compared to the TLD-determined values and assessed against the predetermined 5% tolerance. The results were prepared in the form of an individual certificate that was returned to each participant together with the summary of all results.

4.3.3. Development and testing of the step 2b audit methodology

Seven different DANs were involved in conducting feasibility and pilot studies to assess the functionality and accuracy of the TLD holders used for the audit and of the documentation to measure the dosimetric parameters for non-reference conditions for electron beams proposed within this audit step. These feasibility studies encompassed several tests, such as determining the electron energy dependence of the TLD response [134] and the logistics of mailing the quality audit packages to LCs for this specific audit. During this process, any pitfalls of the proposed approach to these quality audits were identified and corrected. Initial pilot TLD runs were conducted between national systems and the IAEA Dosimetry Laboratory, and then at the national level with a selected number of hospitals to test methods, instructions, data sheets, etc.

It was part of the approach for each of the DANs to perform a pilot run of the step 2b audit for checking electron beam output and dose variation with field size and treatment distance step. In many countries this activity was given lower priority, as it was deemed necessary first to ensure the establishment of photon beam dosimetry audits covering a wider range of clinical dosimetry parameters. However, it was generally agreed that audits for electron beams were still needed to ensure the safe delivery of

radiotherapy doses to patients. The work carried out within the framework of the CRP included extensive development and testing, not only of the methods and phantoms for hospital irradiations and of new documentation, but also of the methods and correction for the evaluation of the TLD dosimeters for electron beams, as this was a new application for the IAEA based TLD system as well as for the DANs. This detailed work was all necessary before the practical audits could be carried out.

4.3.4. Results of the national runs for the step 2b audit

The following summarizes the results and experience from four countries participating in the CRP whose DANs performed step 2b audit pilot runs.

The results seen in Fig. 8 showed very good agreement for checks of electron beam output in reference conditions for energies ranging from 6 MeV to 20 MeV with an overall average of near unity and an SD of less than ±0.02.

Two countries were able to progress beyond just verifying the electron beam outputs to also include checks of electron dosimetric parameters in non-reference conditions. Country 3 checked non-reference parameters for 32 beams and country 4 checked parameters for 40 beams as part of national runs, in addition to checking beam outputs in reference conditions. All beam output checks were within the 5% criterion except for two results (Fig. 8) in country 4 that showed deviations just outside the 5% limit. They had follow-up actions and these discrepancies were resolved in a second check. The results in country 4 showed a mean ratio of 1.00 ± 0.02. In addition, the 40 electron beams that had non-reference parameters tested in country 4 were limited to only checking the 6 × 6 cm^2 field size variation in dose. No deviations outside 5% were observed in these non-reference condition checks. The non-reference results showed a mean ratio of 1.00 ± 0.02.

4.3.5. Summary and conclusions for the step 2b audit

Within the second CRP, few countries chose to focus activities on the development of audits in reference and non-reference conditions for electron beams compared to extending the scope of audits for high energy photon beams. This activity was typically given lower priority, as it was deemed necessary first to ensure the establishment of photon beam dosimetry audits covering a wider range of clinical dosimetry parameters because the large majority of patient treatments use photon beams. Also, many treatment units, including all cobalt units and lower MV X ray linacs, do not provide electron

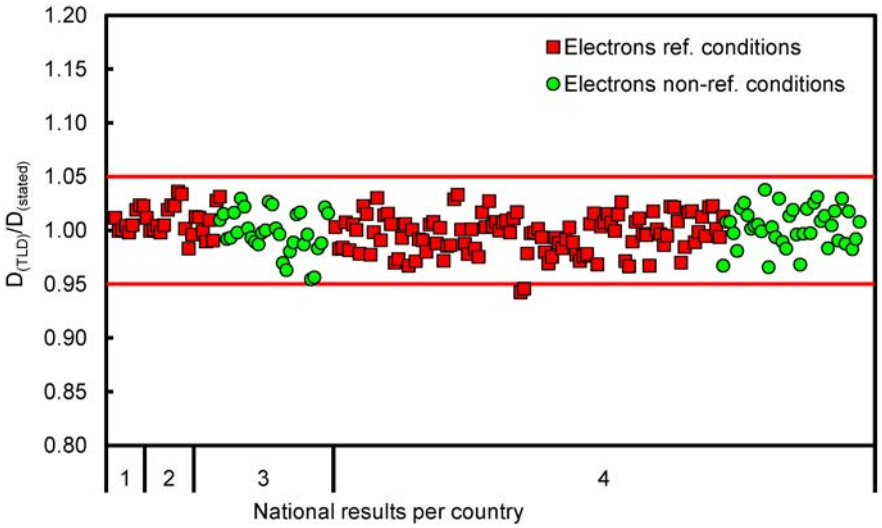


FIG. 8. Results of national runs for TLD audits performed in reference and non-reference conditions for high energy electron beams.

beams, of course. However, it was generally agreed that audits for electron beams were needed, as a rapidly increasing number of linacs providing electron beams, as well as high energy X ray beams, were installed throughout the world and the same levels of QA and quality audit are necessary for their safe and effective use.

The work carried out within the framework of the step 2b audit included establishing methods of use and evaluation of the TLDs for electron beams, as this was a new application for the CRP participants. In particular, new phantoms and methods were designed, developed and tested; correction factors for the TLD capsules in electron beams were tested; energy correction factors and other corrections for the response of the TLD in this application were determined for electron beam use, and a new methodology was developed and tested for the hospital irradiations for the TLD-based audits for electron beams. The last of these needed a new set of documentation, including instructions, data sheets, result reporting forms, etc., all of which had to be adapted into usable forms for each country and tested for practical use.

Of the countries participating in the CRP that chose to work on electron beam audits, most carried out only feasibility or pilot studies. Overall, the results in electrons were not significantly different from those observed in similar feasibility or pilot study audits for photon beams, implying that the level of quality in electron beam dosimetry is similar to that in photon beam dosimetry. Mean ratios were close to unity (1.00 to 1.01) and SDs were also similar (0.01 to 0.02) to those in the photon beam reference condition pilot studies. All countries involved reported that the methods were feasible to extend to the national level within their national DAN structure.

The instruction sheets, data sheets and results reporting forms that were prepared for audit step 2b to specify the irradiation conditions and collect the necessary irradiation information (Package 4) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.4. STEP 3: AUDITS FOR PHOTON BEAMS IN REFERENCE CONDITIONS AND NON-REFERENCE CONDITIONS OFF-AXIS

4.4.1. Introduction to the step 3 audit

It was determined, through previous experiences reported by some national audit networks, that many deviations occur in situations different from reference, and they represent common clinical scenarios. It has been concluded that an external independent audit is necessary for at least some non-reference situations, to complement the basic dosimetry audit in reference conditions. The step 3 audit was developed to check the dosimetry of high energy photon beams under reference and non-reference conditions with a specific focus on 'off beam axis' dosimetry parameters in symmetric and asymmetric fields. As such, step 3 represents an extension of step 2, also developed under the same CRP (E2.40.12, Development of TLD-Based Quality Audits for Radiotherapy Dosimetry in Non-reference Conditions). This quality audit step is intended to be carried out by all hospitals, for those selected photon beams used most often clinically. The audit was tested at the national level in the following countries: Algeria, Argentina, Bulgaria, China, India and Poland.

4.4.2. Methodology of the step 3 audit

The purpose of this TLD audit is to check the dose delivered by the radiotherapy unit in symmetric fields on- and off-axis, as well as in asymmetric fields, with and without wedges, at 10 cm depth in water, in either a fixed SSD or SAD set-up. The quality audit step 3 is separated into two parts, one for symmetric (part 1) and one for asymmetric (part 2) fields.

For the step 3 audit a special version of the IAEA standard dosimeter holder with a horizontal arm was developed at the IAEA. As can be seen in Fig. 9 (reproduced from Ref. [106]), the modified holder enables measurements in non-reference conditions, on- and off-axis (i.e. up to three TLDs can be

irradiated at the same time with two TLDs placed at 5 cm off-axis from the central TLD). The horizontal arm consists of two tubes rigidly connected to a PMMA disc, with an additional hole for fixing to the vertical central tube. Three colour-coded TLD capsules (blue, red, green) were introduced so that the individual TLDs put in different off-axis positions can be easily identified.

The measurements using the modified holder are performed with its vertical tube positioned on the central (collimator rotational) axis, and the irradiation time or number of monitor units (MU) is calculated to irradiate the central TLD with the dose of 2 Gy for all cases as described below.

Quality audit step 3, part 1 in symmetric fields involves the following settings, as described in Ref. [106]:

"The TLD irradiation session consisted of the following steps:

— Beam output in reference conditions: a TLD at 10 cm depth; 10 × 10 cm^2 field; this measurement is carried out twice.
— Open field profile: three TLDs (central on-axis and ±5 cm off-axis); 20 × 20 cm^2 field; holder positioned such that its arm lies along a major field axis (e.g. X-axis, [Fig. 10]). This measurement is repeated with three new TLDs after rotating the holder through 90°, to check the other major field axis (e.g. Y-axis, [Fig. 11]).
— Wedged field profile: three TLDs (central on-axis and ±5 cm off-axis); holder positioned such that the arm lies along the direction of the wedge slope (i.e. such that the axis of each TLD is perpendicular to the slope of the wedge). Field size for accelerators: 20 × 20 cm^2 and the most commonly used wedge; for cobalt units: 15 × 20 cm^2, the most commonly used wedge that completely covers the 15 cm field in the direction of the slope of the wedge [Fig. 12]."

FIG. 9. Modified standard TLD holder for off-axis measurements with photon beams (reproduced from Ref. [106]).

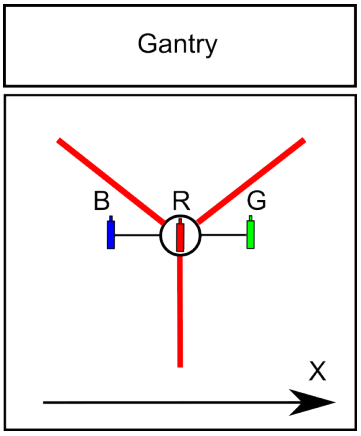


FIG. 10. Alignment of the holder tube, viewed from above the phantom for measurements of the open symmetric profile in the X direction; B — blue, R — red, G — green.

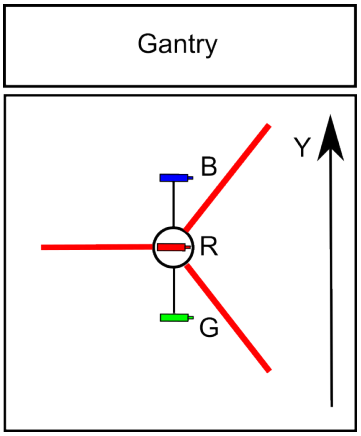


FIG. 11. Alignment of the holder tube, viewed from above the phantom for measurements of the open symmetric profile in the Y direction; B — blue, R — red, G — green.

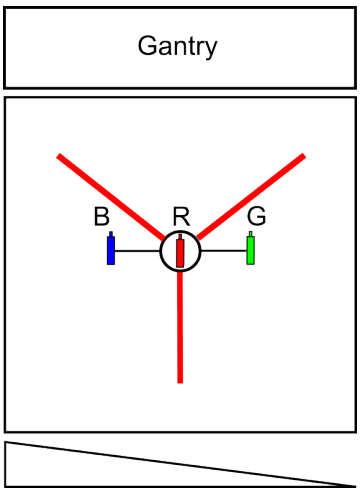


FIG. 12. Alignment of the holder tube, viewed from above the phantom for measurements of the wedged beam profile; B — blue, R — red, G — green.

Quality audit step 3, part 2 in asymmetric fields involves the following settings:

— Beam output measurements in reference conditions: TLD positioned at 10 cm depth in the TLD holder without horizontal arm; irradiation in 10 × 10 cm^2 field; this measurement is carried out twice.
— Open asymmetric field profile: Two TLDs (central on-axis and +5 cm off-axis) in an offset field; The TLDs need to be irradiated with a 10 × 10 cm^2 field, but offset in one direction by 2.5 cm such that the first TLD is positioned on the central axis and the second TLD is shifted 5 cm from the central axis inside the field (Fig. 13(a)). In cases where asymmetric collimation is not possible, a symmetric field size of 15 cm × 10 cm should be used and a block positioned to shield 5 cm from one edge of the 15 cm dimension (Figs 14(a) and (b)). The holder has to be positioned such that its arm lies along the major field axis in the direction of the asymmetric offsets (e.g. X-axis).
— Wedged asymmetric field profile: Two TLDs (central on-axis and +5 cm off-axis) in an offset field; The TLDs need to be irradiated with a 10 × 10 cm^2 field, but offset in one direction by 2.5 cm such that the first TLD is positioned on the central axis and the second TLD is shifted 5 cm from the central axis inside the field (Fig. 13(b)). In cases where asymmetric collimation is not possible, a symmetric field size of 15 cm × 10 cm needs to be used and a block positioned to shield 5 cm from one edge of the 15 cm dimension (Figs 14(c) and (d)). The offsets and the holder positioning are in the direction of the wedge slope and such that the offset and the measurements are towards the thick end of the wedge. The most commonly used wedge that completely covers the fields is to be used.
— Dose measurements in a half beam blocked open field: The TLD is positioned in the centre of a 10 × 10 cm^2 field but offset by 5 cm (Figs 15(a) and (b)). It is achieved by positioning the holder on the central axis and inserting the TLD into the slot of the holder's arm. In cases where asymmetric collimation is not possible, a symmetric 20 cm × 10 cm field needs to be set and a block positioned to shield half of the field.
— Dose measurements in a half beam blocked wedged field: The TLD is positioned in the centre of a 10 × 10 cm^2 field but offset by 5 cm (Figs 15(c) and (d)). It is achieved by positioning the holder on the central axis and inserting the TLD into the slot of the holder's arm. In cases where asymmetric collimation is not possible, a symmetric 20 cm × 10 cm field needs to be set and a block positioned to shield half of the field. The offsets and the holder positioning are in the direction of the wedge slope and such that the offset and the measurements are towards the thick end of the wedge. The most commonly used wedge that completely covers the fields is to be used.

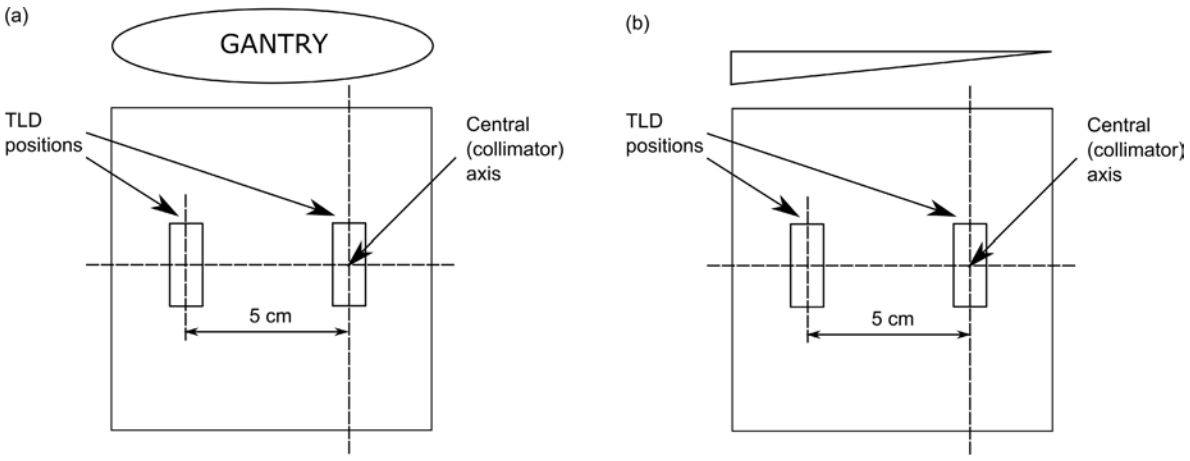


FIG. 13. Schematic illustration of the set-up for (a) asymmetric open and (b) wedged fields, beam view, keeping the same collimator rotation.

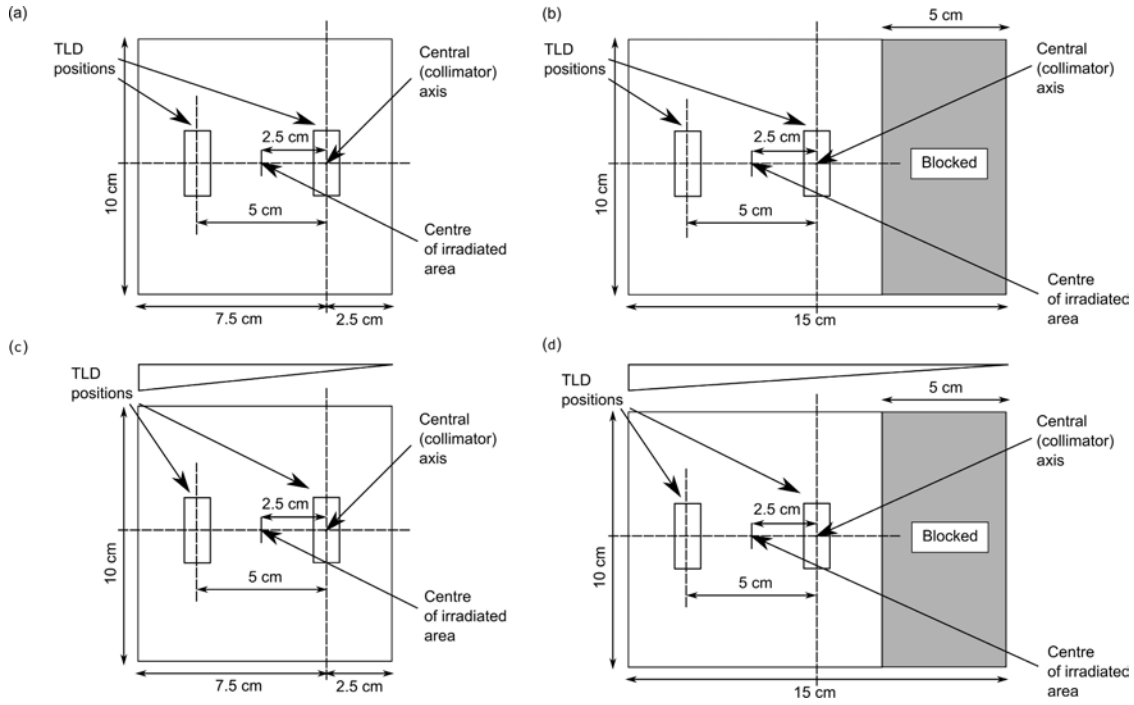


FIG. 14. Set-up for asymmetric open field: (a) where asymmetric collimators are available (beam view); (b) where asymmetric collimators are NOT available and blocking is used (beam view). Set-up for asymmetric wedged field: (c) where asymmetric collimators are available (beam view); (d) where asymmetric collimators are NOT available and blocking is used (beam view).

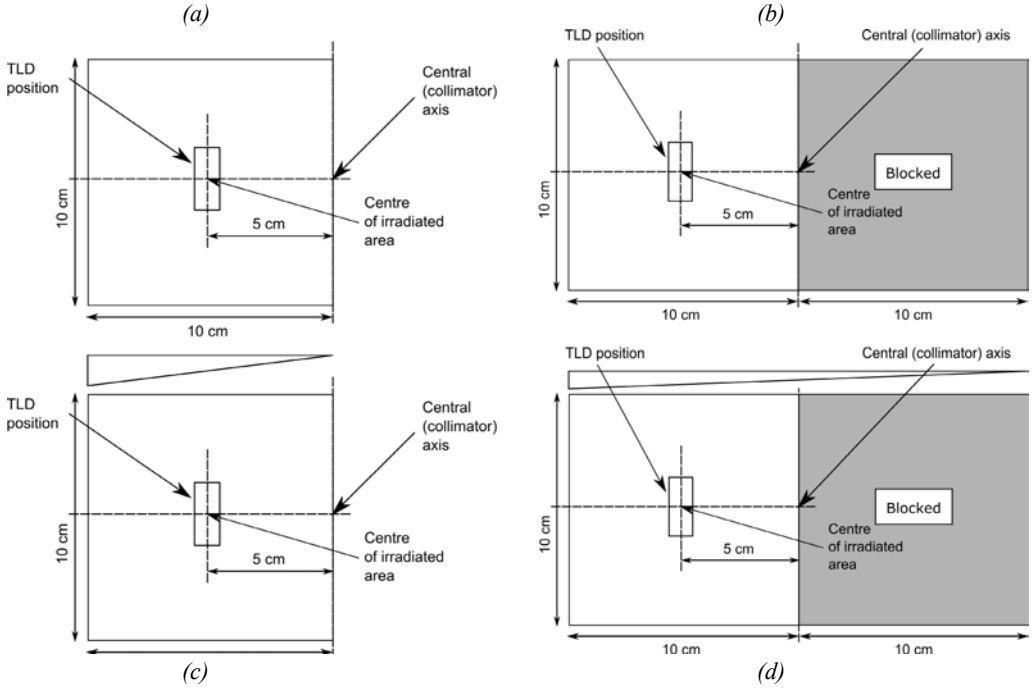


FIG. 15. Set-up for half beam blocked open field: (a) where asymmetric collimators are available (beam view); (b) where asymmetric collimators are NOT available and blocking is used (beam view). Set-up for half beam blocked wedged field: (c) where asymmetric collimators are available (beam view); (d) where asymmetric collimators are NOT available and blocking is used (beam view).

4.4.3. Development and testing of the step 3 audit methodology

4.4.3.1. Feasibility study of modified TLD holder

In a first step, the prototype of the modified TLD holder was evaluated with respect to feasibility and accuracy for the dose audit in non-reference conditions [106]. A series of tests were conducted using a range of high energy photon beams available at the Medical University of Vienna/AKH Vienna. The following beam qualities were used for the testing of the modified TLD holder: a ^{60}Co beam from a Theratron 780 Elite unit (Theratronics, Canada), and 6 MV, 10 MV and 25 MV provided by an Elekta SLi linac (Elekta, UK). Absorbed dose determination was performed according to the IAEA's TRS-398 with a calibrated Farmer type IC [109]. Relative dose measurements were performed using the Farmer type IC and an IC of 0.3 cm^3 volume.

The following detailed explanation of the measurements performed is given in Ref. [106] and refer to a fixed SSD set-up with the top of the TLD holder (and the water surface) at 100 cm SSD for the linac and at 80 cm SSD for the cobalt unit:

> "As the TLD holder is made of a PMMA tube of 1 mm thick walls and the tube above the central TLD is 10 cm long, there is additional beam attenuation that results in a smaller dose delivered to the part of the TLD shielded by the PMMA tube. This partial shielding effect has to be corrected for when evaluating the TL-readings [thermoluminescence readings] to obtain the absorbed dose to water at the position of the TLD in the phantom in the absence of the holder. The holder correction is defined as the ratio of the dose with no TLD holder in the photon beam to the dose with the holder… the shielding of the TLD by the holder tube was determined from the interpolation of the holder effect measured with a Farmer type chamber and with the smaller chamber with a greater volume shielded by the holder tube, e.g. an ionisation chamber with 0.3 cm^3 volume…In order to test this experimentally and to determine perturbation factors and holder correction factors, the holes in a holder were enlarged to allow ionization chambers to be placed at the TLD position in the holder tube.
>
> The beam attenuation by the holder tube depends on the photon beam quality. Therefore measurements were performed at 10 cm depth for field sizes of 10 × 10 cm^2 and 20 × 20 cm^2 in all four beam qualities. In order to determine the effect of beam quality modifications introduced by the wedge, measurements were repeated in wedged beams (60° wedge) of the same field sizes on the linac. On the cobalt [^{60}Co] unit, measurements were performed using a 45° wedge for the standard 10 × 10 cm^2 field and the largest wedged field of 15 × 20 cm^2 available on this machine. These measurements were conducted for the holder both with and without the horizontal arm in place to assess the effect of the arm, if any. Note that the holder correction is to be applied for the central TLD position only. The off-axis TLDs lie partly beneath a 1 mm PMMA layer, the effect of which can be disregarded, because it represents only the excess beam attenuation by 0.02 g/cm^2."

Determination of the holder correction for TLD measurements was done in two steps: first, the holder effect as a ratio of IC readings without and with the holder in place was estimated for two ICs of 0.6 cm^3 and 0.3 cm^3 volumes; next, the shielding of the TL powder by the walls of the holder tube from IC measurements was derived, considering the fraction of the volume shielded in all cases. Figure 16(a) (reproduced from Ref. [106]) shows the holder perturbation effect measured with 0.6 cm^3 Farmer chamber at 10 cm depth as a function of beam quality for a holder without its horizontal arm. The values presented are the average values from five measurements per field (SD per set-up smaller than 0.2%). The holder effect has nearly linear dependence on beam energy and decreases from 1.017 for ^{60}Co to 1.005 for 25 MV. The holder effect determined in open or wedged beams of the same field size were almost indistinguishable. All deviations between the beam perturbations determined at different field sizes were below 0.3% for a given photon beam energy.

Figure 16(b) (reproduced from Ref. [106]) shows the results of a similar set of measurements for the modified TLD holder, including its horizontal arm.

To get the TLD holder correction factor, the interpolation of the two chamber readings was made according to the ratios of the shielded volume to the total volume V_{sh}/V_{tot} for the chambers and the TLD [87].

Table 4 (reproduced from Ref. [106]) presents correction factors of the modified TLD holder as a function of beam quality. It can be noted that the corrections are small and the addition of the horizontal arm has almost no effect. It has therefore been decided to use one averaged set of data for further applications, and the values used are given in the last line.

4.4.3.2. Feasibility study on symmetric fields with TLD measurement on- and off-axis

In this feasibility study the reproducibility, accuracy and workload of TLD measurements were evaluated in the non-reference conditions at points located on-axis and off-axis using high energy

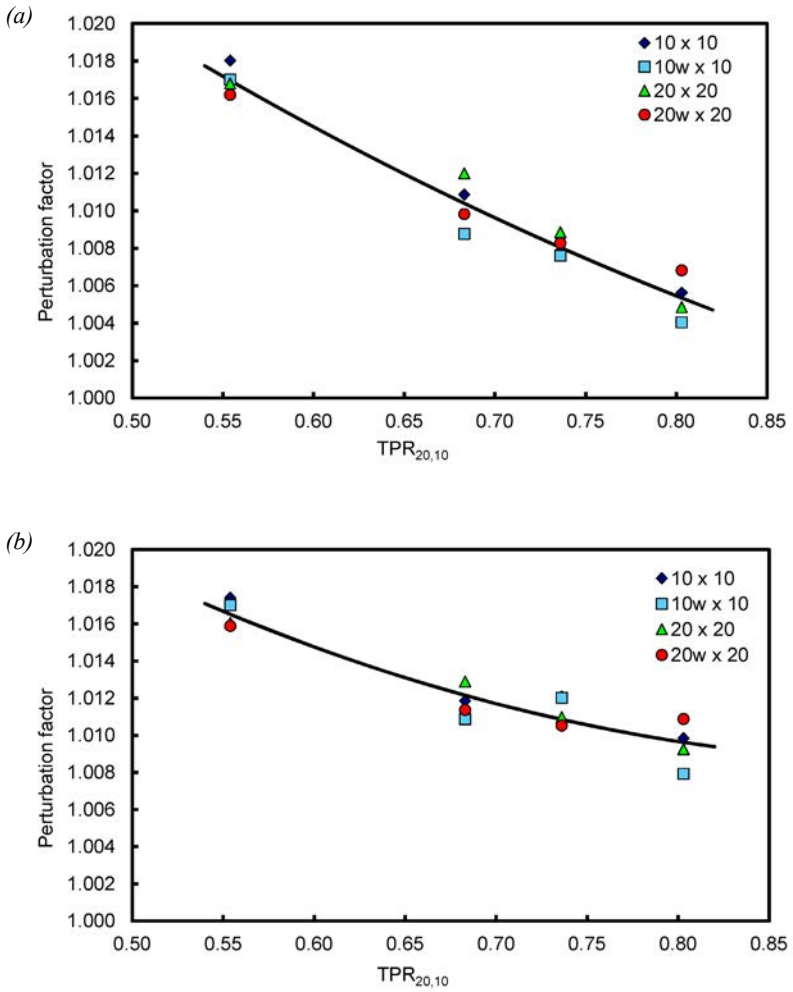


FIG. 16. Perturbation factors of the modified TLD holder at 10 cm depth as a function of $TPR_{20,10}$, the tissue–phantom ratio in water at depths of 20 and 10 g/cm^2, for a field size of 10 cm × 10 cm and a fixed source detector distance of 100 cm, which is used as the beam quality index for linac photon beams. The $TPR_{20,10}$ for Co-60 is plotted as 0.556. The factors are determined in open and wedged 10 × 10 cm² and 20 × 20 cm² fields: (a) for the TLD holder without its horizontal arm; (b) for the TLD holder with its horizontal arm in place (reproduced from Ref. [106]).

TABLE 4. PERTURBATION CORRECTION FACTORS OF THE MODIFIED TLD HOLDER AS A FUNCTION OF $TPR_{20,10}$ DETERMINED USING INTERPOLATION METHODS BASED ON MEASUREMENTS WITH TWO IONIZATION CHAMBERS IN 10 × 10 cm^2 AND 20 × 20 cm^2 OPEN FIELDS
(*reproduced from Ref. [106]*)

Dosimeter	Fraction of shielded volume				
		Holder without horizontal arm			
		Co-60	6 MV $TPR_{20,10}$ = 0.683	10 MV $TPR_{20,10}$ = 0.736	25 MV $TPR_{20,10}$ = 0.803
Ion chamber 0.6 cc	0.18	1.017	1.011	1.008	1.005
Ion chamber 0.3 cc	0.32	1.021	1.015	1.011	1.007
TLD interpolated	0.21	1.018	1.012	1.009	1.006
		Holder with horizontal arm			
Ion chamber 0.6 cc	0.18	1.017	1.013	1.011	1.009
Ion chamber 0.3 cc	0.32	1.021	1.012	1.011	1.010
TLD interpolated	0.21	1.017	1.013	1.011	1.009
Averaged set with or without horizontal arm		1.017	1.012	1.010	1.008

photon beams of ^{60}Co, 6 MV, 10 MV and 25 MV. Results obtained for symmetric fields are shown in Table 5 and Table 6 (reproduced from Ref. [106]). Ratios of the TLD-measured dose relative to the IC determined dose are calculated for each measurement point and for the wedge transmission factors, output factors and off-axis ratios. Details of the results are thoroughly discussed in Ref. [106]; to sum up, TLD measurements were found to be in very good agreement with IC measurements for all irradiation scenarios and beam qualities.

4.4.3.3. Feasibility study for asymmetric fields with TLD measurement on- and off-axis

As a further separate step in the feasibility study of the procedures, the methodology was tested for asymmetric beams using exactly the same methods as described above for symmetric beams. The summary of results from up to five test sessions performed during 2002–2005 for a range of high energy photon beams is given in Table 7. Each data point represents an average of up to 15 TLDs (i.e. three TLDs per measurement point per session). As for the symmetric fields, ratios of the dose off-axis to that on-axis are given for both TLD and IC measurements for the offset field and are compared with each other. For the half beam blocked field dose ratios $D_{(TLD)}/D_{(IC)}$ 5 cm off-axis are given.

Most measured $D_{(TLD)}/D_{(IC)}$ ratios for asymmetric fields were within ±1% of unity (range 0.986–1.014), with an overall mean of 0.998 ± 0.009, showing that the TLD results in these fields also follow closely the IC measurements. The set-up and alignment of the holder was more difficult, especially

TABLE 5. RATIOS OF TLD AND IONIZATION CHAMBER MEASUREMENTS FOR SYMMETRIC FIELDS ON-AXIS IN NON-REFERENCE CONDITIONS FOR HIGH ENERGY PHOTON BEAMS OF Co-60, 6 MV, 10 MV AND 25 MV
(*reproduced from Ref. [106]*)

Field	Co-60	6 MV $TPR_{20,10}$ = 0.683	10 MV $TPR_{20,10}$ = 0.736	25 MV $TPR_{20,10}$ = 0.803	Mean
(a) Dose on-axis			$D_{(TLD)}/D_{(IC)}$		
10 × 10 cm^2	1.008	1.000	0.992	1.003	1.001
10w × 10 cm^2	1.005	0.997	0.986	0.992	0.995
20 × 20 cm^2	1.010	1.007	1.000	1.008	1.006
20w* × 20 cm^2	1.008	0.994	0.989	1.001	0.998
Mean	1.008	1.000	0.992	1.001	1.000
(b) Wedge transmission			$[D_{wedge}/D_{open}]^{TLD}/[D_{wedge}/D_{open}]^{IC}$		
10w × 10 cm^2	0.996	1.004	0.991	0.993	0.996
20w* × 20 cm^2	1.001	0.996	0.991	1.001	0.997
Mean	0.998	1.000	0.991	0.997	0.997
(c) Output factors			$[D_{(20\times20)}/D_{(10\times10)}]^{TLD}/[D_{(20\times20)}/D_{(10\times10)}]^{IC}$		
Open	1.002	1.006	1.008	1.004	1.005
Wedged	1.005	0.989	1.002	1.009	1.001
Mean	1.003	0.998	1.005	1.007	1.003

* Co-60 15w × 20 cm^2.

for the half beam blocked fields, and gave rise to more detailed instructions for this in the subsequent pilot and national test runs.

4.4.3.4. Multicentre pilot with the modified TLD holder in symmetric and asymmetric fields

The audit methodology was tested in 2004–2005 in a multicentre pilot study. Radiotherapy centres from Algeria, Argentina, Bulgaria, Cuba, China, India, Poland, the hospital network participating in audits performed by the Equal laboratory and the National Cancer Centre in Hungary (nine countries altogether) took part in the study. Overall, 20 high energy photon beams with energies ranging from ^{60}Co to 23 MV were used to test the methodology.

The packages containing TLDs, the modified holders, TLD instructions and data sheets were prepared by the IAEA Dosimetry Laboratory and posted to participants. Upon return, dosimeters were evaluated and dosimetric parameters were derived. Comparisons of the participants' stated values and the TLD-determined values were performed, and their ratios $D_{(TLD)}/D_{(stated)}$ were recorded as results of the methodology testing. The determined values for reference conditions were taken as the average of two TLD measurements, while only one TLD was used to measure the values in non-reference conditions.

TABLE 6. RATIOS OF TLD AND IONIZATION CHAMBER MEASUREMENTS FOR SYMMETRIC FIELD BEAM PROFILES (OFF-AXIS TO ON-AXIS POINTS) FOR 20 × 20 cm^2 OPEN AND WEDGED FIELDS FOR CO-60 AND 6 MV, 10 MV AND 25 MV PHOTON BEAMS (*reproduced from Ref. [106]*)

(a) Beam profile, 20 × 20 cm^2 open field, off-axis ratio

	D(–5)/*D*(0)			*D*(5)/*D*(0)		
Beam	IC	TLD	TLD/IC	IC	TLD	TLD/IC
Co-60*	0.962	0.973	1.011	0.965	0.976	1.011
6 MV, $TPR_{20,10} = 0.683$	1.012	1.018	1.006	1.008	1.011	1.004
10 MV, $TPR_{20,10} = 0.736$	1.019	1.023	1.004	1.015	1.024	1.009
25 MV, $TPR_{20,10} = 0.803$	1.038	1.038	1.000	1.037	1.028	0.991
Mean			1.005			1.004

(b) Beam profile, 20 × 20 cm^2 wedged field, off-axis ratio

	D(–5)/*D*(0)			*D*(5)/*D*(0)		
Beam	IC	TLD	TLD/IC	IC	TLD	TLD/IC
Co-60*	1.186	1.193	1.005	0.790	0.780	0.987
6 MV, $TPR_{20,10} = 0.683$	1.205	1.200	0.996	0.856	0.852	0.995
10 MV, $TPR_{20,10} = 0.736$	1.214	1.224	1.009	0.861	0.864	1.003
25 MV, $TPR_{20,10} = 0.803$	1.266	1.275	1.007	0.874	0.872	0.997
Mean			1.004			0.995

* Co-60 15w × 20 cm^2.

The results of the multicentre pilot study of the audit methodology are shown in Fig. 17 (reproduced from Ref. [106]). The testing results for reference conditions, non-reference conditions on- and off-axis for open symmetric fields, and on- and off-axis for wedged symmetric fields are shown in Fig. 17(a) (reproduced from Ref. [106]). In total, 209 measurement results were obtained, and the mean ratio of measured dose to the participant-stated dose was 0.999 ± 0.013 (1 SD). Results grouped by the parameter evaluated had different statistical distributions, with the SD ranging from 0.011 for open fields to 0.015 for wedged fields.

The results of the methodology testing for auditing relative beam parameters (i.e. off-axis ratios for open and wedged symmetric fields at –5 cm and +5 cm, $[D(-5)/D(0)]^{TLD}/[D(-5)/D(0)]^{stat}$ and $[D(+5)/D(0)]^{TLD}/[D(+5)/D(0)]^{stat}$, relative output factors for 20 × 20 cm^2 open fields, $[D_{(20\times20)}/D_{(10\times10)}]$

TABLE 7. RATIOS OF TLD AND IONIZATION CHAMBER MEASUREMENTS FOR ASYMMETRIC FIELD BEAM PROFILES (OFF-AXIS TO ON-AXIS POINTS) FOR THE OPEN AND WEDGED 10 × 10 cm^2 OFFSET FIELDS AND DOSE RATIOS (TLD/IC) FOR THE 10 × 10 cm^2 HALF BEAM BLOCKED FIELDS FOR CO-60 AND 6 MV, 10 MV AND 25 MV PHOTON BEAMS

(a) Beam profile, offset field, off-axis ratio

	$D(-5)/D(0)$ open field			$D(-5)/D(0)$ wedged field		
Beam	IC	TLD	TLD/IC	IC	TLD	TLD/IC
Co-60	1.000	1.007	1.007	0.816	0.812	0.995
6 MV, $TPR_{20,10}$ = 0.683	1.030	1.044	1.014	0.866	0.876	1.010
10 MV, $TPR_{20,10}$ = 0.736	1.030	1.029	0.999	0.871	0.877	1.007
25 MV, $TPR_{20,10}$ = 0.803	1.062	1.062	1.000	0.899	0.897	0.998
Mean			1.005			1.003

(b) $D_{(TLD)}/D_{(IC)}$ at 5 cm off-axis, half beam blocked field

Beam	Open field	Wedged field
Co-60	-	-
6 MV, $TPR_{20,10}$ = 0.683	0.991	0.991
10 MV, $TPR_{20,10}$ = 0.736	0.992	0.997
25 MV, $TPR_{20,10}$ = 0.803	0.986	1.002
Mean	0.990	0.997

$^{TLD}/[D_{(20\times20)}/D_{(10\times10)}]^{stat}$ and wedge transmission factors $[D_{wedge}/D_{open}]^{TLD}/[D_{wedge}/D_{open}]^{stat}$) are shown in Fig. 17(b) (reproduced from Ref. [106]). The statistical distribution of all ratios, representing 147 measurements of the different beam parameters for all beams, has a mean of 0.999 ± 0.012 (1 SD). Similarly, the results attributed to open fields had smaller SD of 0.011 as compared to the results for wedged fields with SD of 0.015.

The audit methodology for asymmetric fields was tested in 2006 in a second multicentre pilot run. Twenty high energy photon beams ranging from ^{60}Co to 25 MV were used, and the hospitals participated belonged to Algeria, Argentina, Austria, Bulgaria, Cuba, China, India and Poland. The methods were exactly as above for the symmetric field study and utilized eight TLDs per beam, including the two necessary for the linked check in reference conditions. Evaluation of results was performed the same way as previously for the symmetric fields.

The results of the pilot study for the audit methodology for asymmetric fields are shown in Fig. 18. Figure 18(a) presents results of measurements in reference conditions and non-reference conditions on- and off-axis for asymmetric open and wedged fields. In total, 148 results were obtained, and a mean ratio of measured dose to participant-stated dose was 0.999 ± 0.016 (1 SD).

Figure 18(b) shows the results of auditing relative beam parameters for asymmetric fields (i.e. off-axis ratios for open and wedged symmetric fields at –5 cm, $[D(-5)/D(0)]^{TLD}/[D(-5)/D(0)]^{stat}$, and

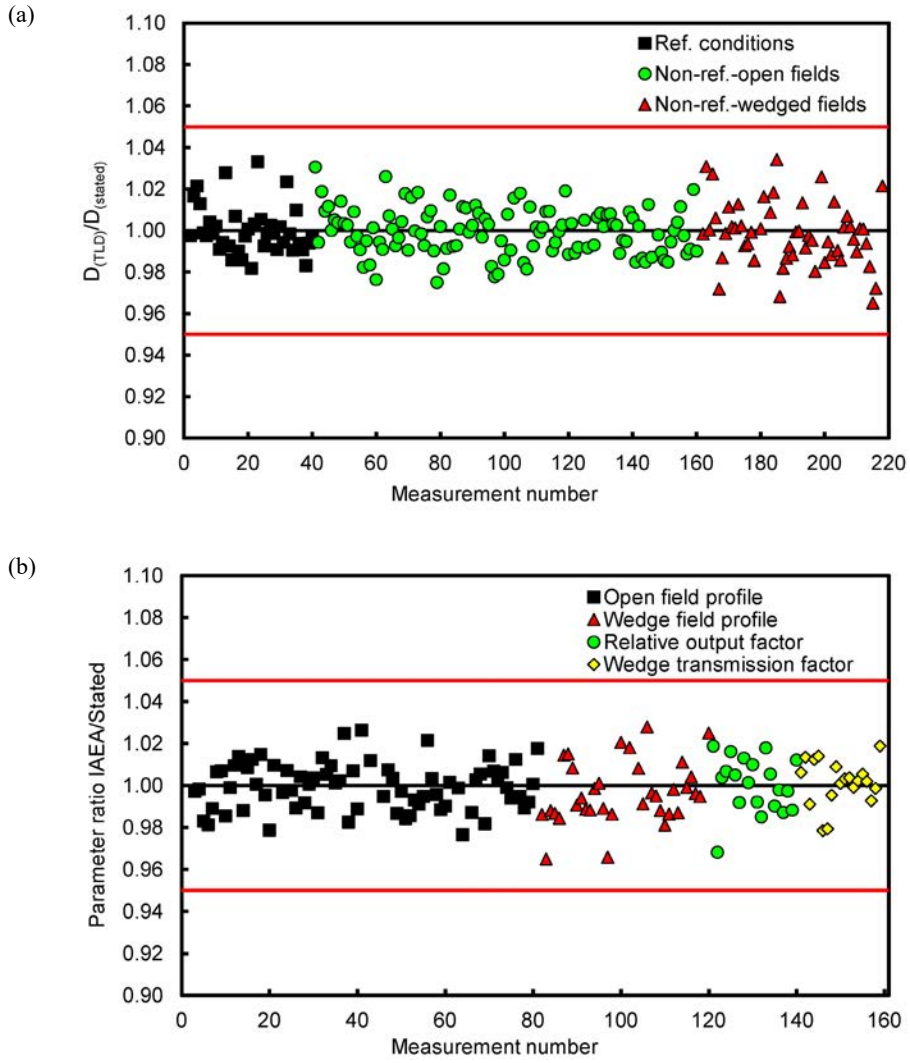


FIG. 17. The results of the multicentre pilot study for non-reference conditions on- and off-axis for symmetric fields: (a) doses (i.e. ratios of the IAEA TLD-measured dose to the participant-stated dose); (b) beam parameters (i.e. ratios of the TLD-measured beam parameter to that stated by the participant) (reproduced from Ref. [106]).

wedge transmission factors, $[D_{wedge}/D_{open}]^{TLD}/[D_{wedge}/D_{open}]^{stat}$). One hundred and eight results had a mean of 0.997 ± 0.016 (1 SD).

4.4.4. Results of the national runs for the step 3 audit

4.4.4.1. Symmetric fields

After the multicentre pilot study had been completed, national runs for step 3 were conducted in six participating countries (Algeria, Argentina, Bulgaria, China, India and Poland). In total, 72 beams were checked. Most results were determined on-axis: 72 in reference conditions, 72 in open fields in non-reference conditions and 64 in wedged fields. Additionally, 275 and 112 off-axis measurements were gathered for open and wedged fields, respectively. The ratios of TLD measurements and dose stated by the user $D_{(TLD)}/D_{(stated)}$ of all beams are depicted in Fig. 19. The mean values and SDs in reference conditions, non-Reference conditions open fields and non-reference conditions wedged fields were 1.003 ± 0.030, 1.008 ± 0.026 and 1.000 ± 0.038, respectively. While the majority of results for the open fields were within the acceptance limit of ±5%, an increased number of wedged fields failed this acceptance limit. However,

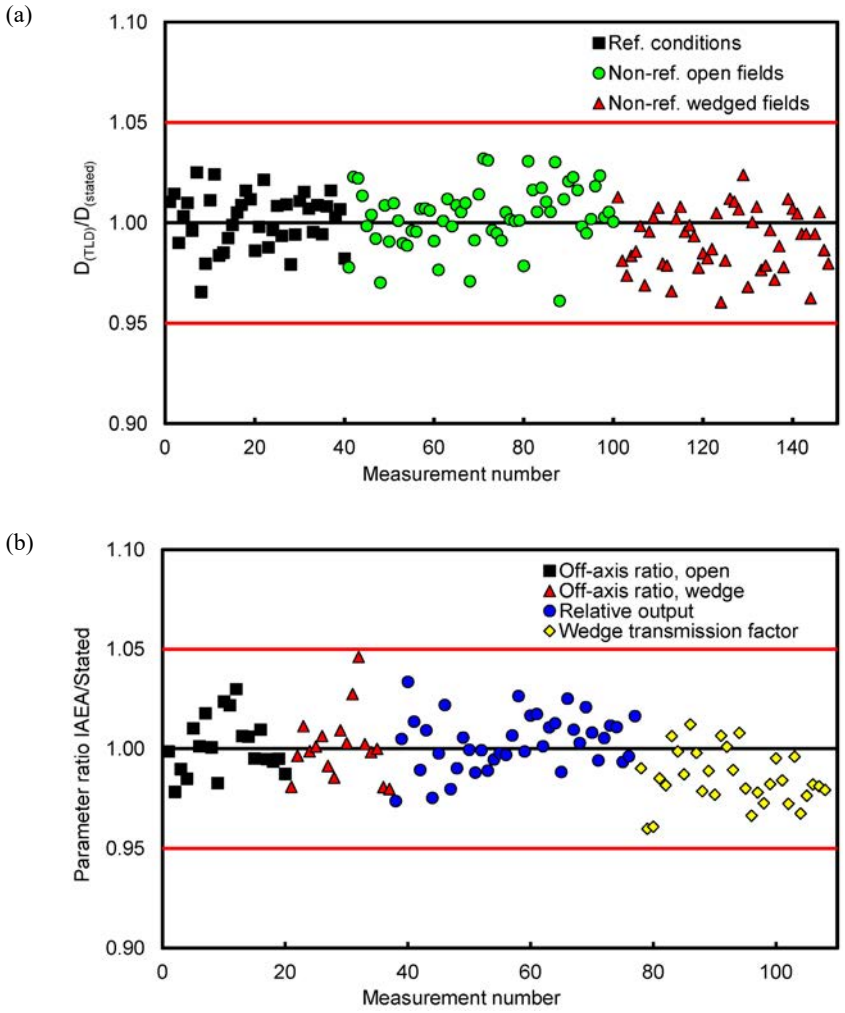


FIG. 18. The results of the multicentre pilot study for non-reference conditions for asymmetric fields: (a) doses (i.e. ratios of the IAEA TLD-measured dose to the participant-stated dose); (b) beam parameters (i.e. ratios of the TLD-measured beam parameter to that stated by the participant).

more than 80% of the wedged field results were within ±5%. Deviations larger than 10% were found in country 5. In this country a self-developed holder was used, not the one available through the CRP.

4.4.4.2. Asymmetric fields

This part of the audit was only conducted in three countries. The results made available by two countries are presented in Fig. 20. One more country reported only general results that three beams were investigated during the audit run and all fields except one were within the tolerance limit. The field exceeding the tolerance limit showed a deviation of 5.2%. Figure 20(a) illustrates the dose ratios of the IAEA TLD-measured dose to the participant-stated dose in reference conditions, in non-reference conditions on- and off-axis for open and wedged symmetric fields, as well as for half beam blocked fields. For country 1, two hospitals participated with four beams in this audit. Two different wedged fields exceeded the acceptance limit, either with respect to the point dose verification $D_{(TLD)}/D_{(stated)}$ or the wedge parameter. In this country also, half-blocked beams were investigated. The results were within the tolerance limit of ±5%. In country 2, six high energy photon beams provided by linacs were included. All results were within the acceptance limit.

A comparison of TLD-measured relative beam parameters to those stated by participants for asymmetric open and wedged fields, as well as half beam blocked fields, are shown in Fig. 20(b). One parameter ratio result in country 1 for asymmetric wedged beams was outside the acceptance limit.

4.4.5. Summary and conclusions for step 3 audit

The modified TLD holder provides a simple yet elegant way to perform measurement off-axis, which can be also mailed the same way as the standard IAEA holder. It is compatible with the earlier audit approaches, and thus easily and cost effectively incorporable into the existing DAN systems. The correction factors determined for the modified TLD holder, cover the clinical range of photon energies.

The multicentre pilot study verified the overall procedure, including the clarity of audit instructions and data sheets, as well as the irradiation and dose evaluation procedures. As the results of the study were found acceptable, the step 3 audit methodology was proved to be feasible. The national results for symmetric fields confirmed the results obtained in the pilot study, with the exception of country 5, where a non-CRP holder was used. Therefore, any deviations from the procedures and methodologies of the steps described in this publication need to be carefully discussed within a DAN, which might necessitate initiatives such as new pilot studies and modifications of instruction sheets. Another outcome of the national runs was the limited participation on asymmetric open and wedged beam checks, which might be explained by the demanding nature of the step 3 audit for asymmetric beams.

However, the step 3 audit methodology is not envisioned to check irregular or small fields related to IMRT, SRS or dynamic wedges, where planar dosimetry with films or detector arrays seems more appropriate.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 3 to specify the irradiation conditions and collect the necessary irradiation information (Package 5) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

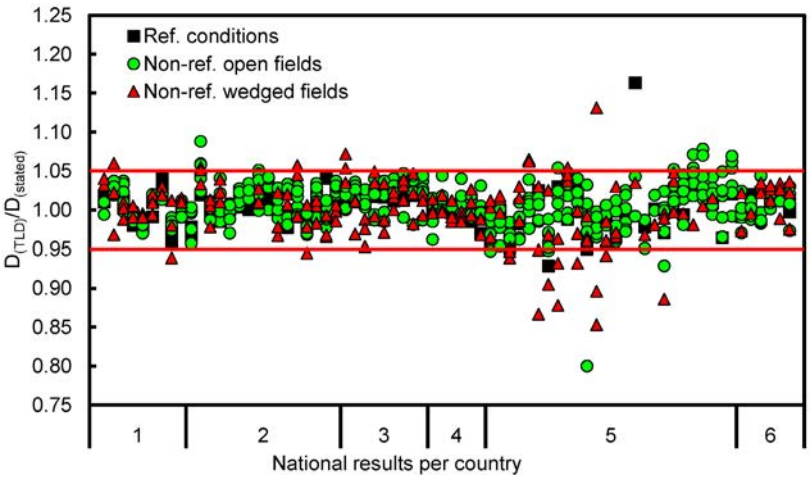


FIG. 19. Results of the ratio of $D_{(TLD)}/D_{(stated)}$ of the national runs by country.

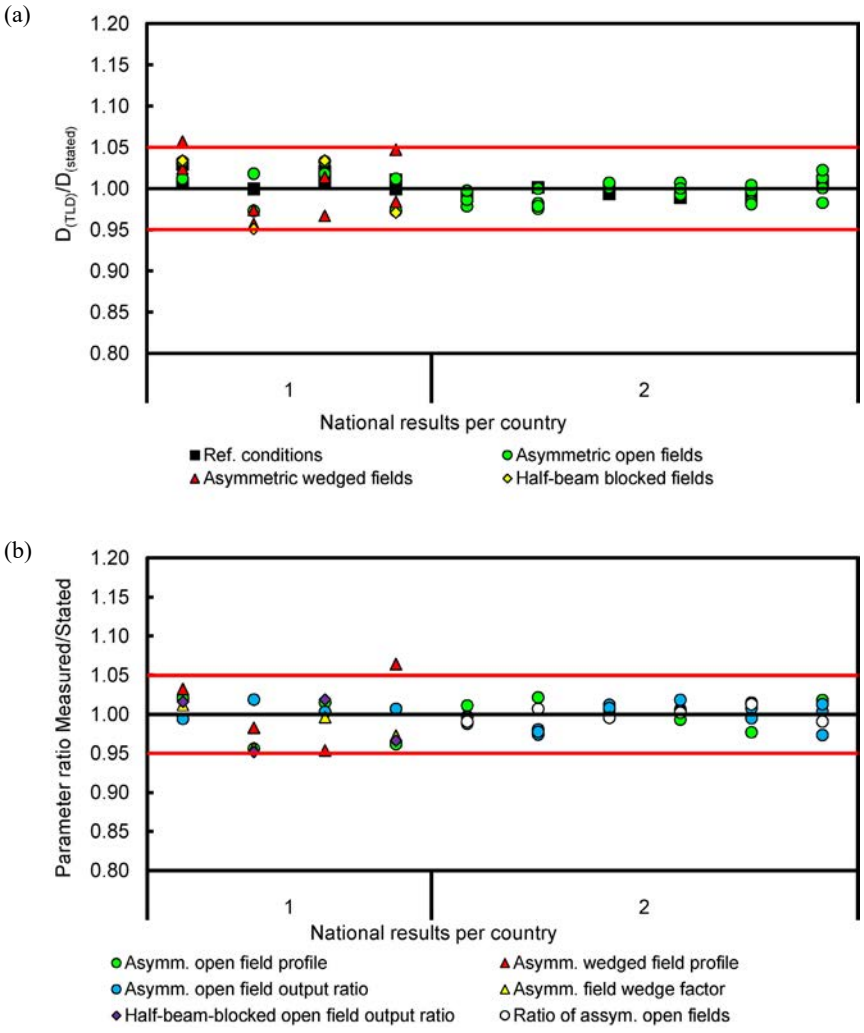


FIG. 20. Results of TLD audits performed for countries in asymmetric beams for high energy photon beams: (a) dose ratios; (b) parameter ratios.

4.5. STEP 4: DOSE AUDITS OF COMPLEX TREATMENT TECHNIQUE PARAMETERS: IRREGULAR PHOTON BEAMS SHAPED WITH AN MLC

4.5.1. Introduction to the step 4 audit

CRP E2.40.16, Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques, was initiated in 2008 and started with the TLD audit of irregular photon beams shaped with an MLC. Its purpose was to check dosimetric data related to radiotherapy treatment units equipped with an MLC. Six participating countries (Algeria, Argentina, Brazil, China, the Czech Republic and Poland) contributed to the CRP and tested newly developed methodology on the national level. The extension of the DAN programme to MLC fields, including irregular fields with and without wedges, took into account the increasing use of these tools in conformal photon beam radiotherapy and as the basis for IMRT. An independent experimental verification of the dose calculated by TPS is an essential step in the improvement of QA in radiotherapy and was therefore an important extension of the DAN programme.

This quality audit step was intended to be carried out for those photon beams in most frequent clinical use. The dose audits for irregular photon beams shaped with an MLC largely followed the previous experience from the Equal-Estro quality audit programme [73].

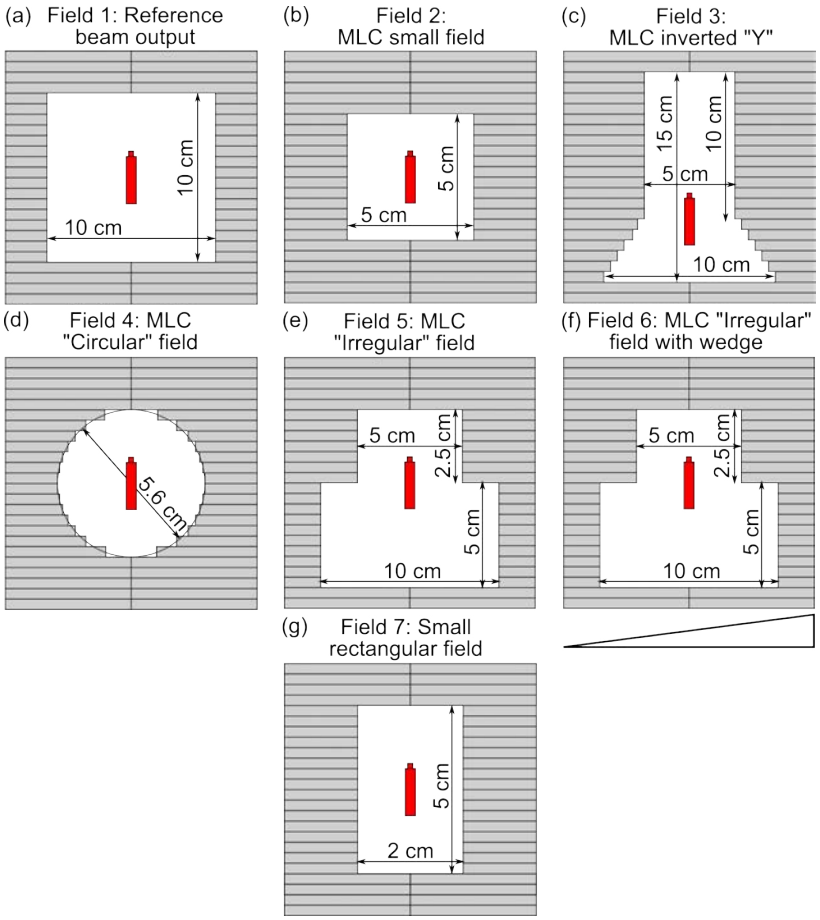


FIG. 21. The seven MLC shaped fields to be used for the quality audit of complex treatments, showing positioning of the TLD.

4.5.2. Methodology of the step 4 audit

This audit step included measured checks of dose variation with specific field sizes and shapes defined by an MLC, including the use of a wedge for one of the MLC shapes. The seven field sizes and shapes defined by the MLC can be seen in Fig. 21. The same standard TLD holder was used as in previous steps 1−2a.

Participating hospitals were requested to provide TPS-calculated absorbed dose values at a depth of 10 cm in water for each of the MLC shapes identified. This allowed the auditors to compare the data used in clinical practice with measured dose values determined with a TLD.

The TLD was positioned in a standard IAEA TLD holder at 10 cm depth in a water phantom, on the beam axis at SAD or SSD, as per the clinical practice of the participating centre. MUs were calculated to deliver the absorbed dose of 2 Gy at the TLD position for each of the following setups:

(a) Reference beam output: 10 × 10 cm^2 field size set with the MLC.
(b) Small MLC field: 5 × 5 cm^2 field size set with MLC.
(c) Inverted Y field: The shape and dimensions of the field size are defined with the MLC.
(d) Circular MLC field: 5.6 cm diameter field size set with the MLC.
(e) Irregular field: The shape and dimensions of the field size are defined with the MLC.
(f) Irregular field with a wedge: The shape and dimensions of the field size are defined by the MLC as shown in Fig. 22, with a wedge commonly used in the clinical practice of the participating centre. MU is calculated to deliver 2 Gy to the TLD by delivering 1 Gy with the wedge in one orientation and then another 1 Gy with the wedge rotated 180 degrees. Note that some accelerator configurations

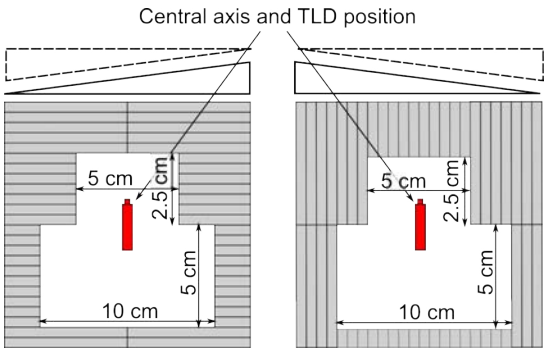


FIG. 22. The irregular MLC shaped field size and wedge configurations with possible variations in leaf direction and wedge orientation for the quality audit of complex treatments.

may need the wedge slope and leaf direction to be perpendicular to each other. The longitudinal axis of the TLD has to be placed perpendicular to the slope of the wedge.

(g) Small rectangular field: 2 × 5 cm^2 field size shaped with the MLC. The longitudinal axis of the TLD has to be placed parallel to the long dimension of the MLC field.

4.5.3. Development and testing of the step 4 audit methodology

A feasibility study was carried out between the IAEA and the Medical University of Vienna/AKH Vienna in 2009. The first tests and irradiations were conducted to assess and provide feedback on the quality audit practicality and functionality and the clarity of the instruction sheets and data forms. Treatment plans were generated using Oncentra MasterPlan for the range of MLC fields for a 6 MV beam and irradiations were carried out on an Elekta Synergy linac. Three TLD measurements were repeated three times for each field size and IC measurements were also carried out for direct comparison. The TLDs were evaluated using the IAEA standard protocol. The results are shown in Table 8, showing generally good agreement between the TLD and IC measurements (mean 0.998, range 0.988–1.009), while the doses measured with an IC were generally lower compared to the TPS-predicted values (mean 0.986, range 0.979–1.000).

TABLE 8. RATIOS OF TLD MEASURED AND TPS CALCULATED DOSES FOR SEVEN IRREGULAR MLC SHAPED FIELD SIZES

Field	$D_{(IC)}/D_{(TPS)}$	$D_{(TLD)}/D_{(IC)}$
Reference conditions (10 × 10 cm^2)	1.000	1.000
Small MLC field (5 × 5 cm^2)	0.984	0.996
“Inverted Y” MLC field (10 × 15 cm^2 Y)	0.995	0.999
Circular MLC field (diameter 5.6 cm)	0.986	1.005
“Irregular” MLC field (7.5 × 10 cm^2)	0.991	0.988
“Irregular” MLC field with wedge (7.5 × 10 cm^2 W)	0.981	0.992
Small rectangular field (2 × 5 cm^2)	0.979	1.009
Mean	0.986	0.998

The methodology, instructions and data sheets were demonstrated to be valid and practical. This was then followed by a multicentre pilot study, with the institutions participating in CRP E2.40.16 representing six countries: Algeria, Argentina, Brazil, China, the Czech Republic and Poland. One centre offered to participate with two machines (four beams). A range of four TPSs were used, with different software versions and dose calculation algorithms. Calculations and irradiations were carried out for a variety of linacs and beam energies, ranging from 6 to 18 MV. Figure 23 summarizes the results for all centres, grouped by beam energy.

In summary, for all participants, the ratio $D_{(TLD)}/D_{(TPS)}$ was within 5% of the TPS dose except for two centres. For centre 2 for 6 MV, the ratio $D_{(TLD)}/D_{(TPS)}$ for the wedged 7.5 × 10 cm^2 was 0.935. However, for this centre the TLD dose was comparable to the IC measured dose (i.e. the ratio $D_{(TLD)}/D_{(IC)}$ was 0.991), indicating that the wedge factor might have been implemented in the TPS incorrectly. For centre 1 for an 18 MV beam the ratio $D_{(TLD)}/D_{(TPS)}$ for the 5 × 5 cm^2 field was 1.057. The ratios for other fields for this energy were also higher (the mean ratio for all fields was 1.027) compared to other participants. The output of the day for this beam was 1.017, which explains the systematic shift of all measurements performed with it.

Three participating centres also provided IC measurement results. All $D_{(TLD)}/D_{(IC)}$ ratios except for one (2 × 5 cm^2 field) were within 5%, with an average of 1.002 and 1.8% SD. Overall, the results were good, and the instruction sheets and data sheet were reportedly easy to follow.

Comments were received about ways to improve the audit methodology, for example by marking the top of the holder to show the direction of the TLD or adding a weight at the bottom of the holder to improve its stability. One participant suggested that it would be useful to include the linac and MLC vendor specific aspects, such as wedge orientation with respect to the direction of leaf motion, on the instruction sheets for field shaping.

Another comment received indicated that the small circular MLC shaped field was challenging to create using a particular TPS. Alternative MLC shaped fields were introduced by some participants, which were also acceptable for this exercise.

4.5.4. Results of the national runs for the step 4 audit

National audit runs were conducted in six participating countries (Algeria, Argentina, Brazil, China, the Czech Republic and Poland). A summary of the number of beams audited and the energies used is

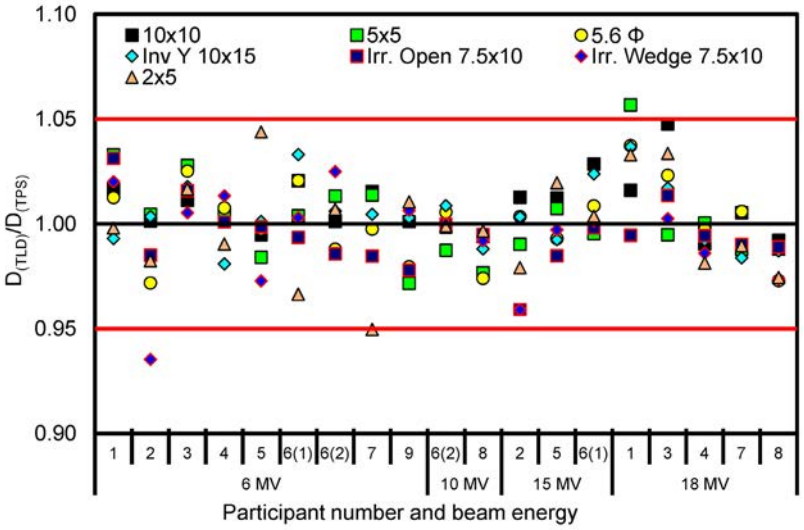


FIG. 23. $D_{(TLD)}/D_{(TPS)}$ results for all centres participating in the multicentre pilot run, grouped by beam energy.

provided in Table 9. In total, all seven MLC shaped fields were checked in 126 beams. The overall results, expressed as the ratio of doses determined by TLD versus TPS, are given in Fig. 24.

The distribution of the overall results of the 727 individual field checks in 126 beams showed a mean of 1.00, an SD of 2.6% and 96% of results within the 5% acceptance limit. Overall, 33 discrepancies were recorded. They were mostly associated with the small rectangular field (n = 11), the combination of an irregular field with a wedge (n = 7) and the circular field (n = 5). Several of these fields caused deviations between the measured and the stated TPS dose that were larger than 10%. These deviations were all followed up by the national DANs. In country 3, all the reported results from one centre were outside the ±5% limit due to TLD holder positioning problems and the exercise needed to be repeated. In the same country a discrepancy was observed for a wedged field, where dosimeter positioning is critical in the dose gradient direction. Also related to wedges but in a different centre, the follow-up of a failing wedged field revealed that an incorrect wedge factor had been input into the TPS. Positioning errors were identified as a potential source of error for the small fields in a few countries.

4.5.5. Summary and conclusions for the step 4 audit

The step 4 audit represented an extension of the non-reference on-axis methodology, using the standard IAEA photon beam TLD holder allowing relatively rapid implementation. The multicentre pilot study, which also included IC measurements, confirmed that these beam checks, including the newly developed instruction and data sheets, were appropriate for wider use.

The irregular MLC shaped fields, which were partly based on the Equal-Estro audit methodology, were found to provide a sufficiently robust set for testing of the combined TPS modelling, dose calculation and beam delivery systems for MLC fields [73]. The set of recommended MLC fields tested different field sizes, shapes, degrees of irregularity and wedge factors.

The minimum field size for this step was, at the time, small enough to test the range below ‘conventional’ field sizes, yet with shapes and dimensions to ensure the TLD capsules were appropriately irradiated. The seven fields were found to ensure a range of clinically relevant conditions, but not in such a large group that overall workload and irradiation time for the audit would be too great. Provided that the dosimeters are appropriately aligned, the audit methodology was shown to be able to identify errors related to the modelling of small, irregular or wedged fields.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for the audit step 4 to specify the irradiation conditions and collect the necessary irradiation information (Package 6) are a part of the on-line supplementary files (which can be found on the publication’s individual web page at www.iaea.org/publications).

TABLE 9. STEP 4 AUDIT: SUMMARY OF BEAMS AUDITED BY COUNTRY IN NATIONAL RUNS

Country	Number of beams audited	Energies (MV)
1	5	6, 18
2	6	6
3	37	6, 10, 15
4	44	6, 10, 15, 18
5	6	6, 18
6	28	6, 15, 18

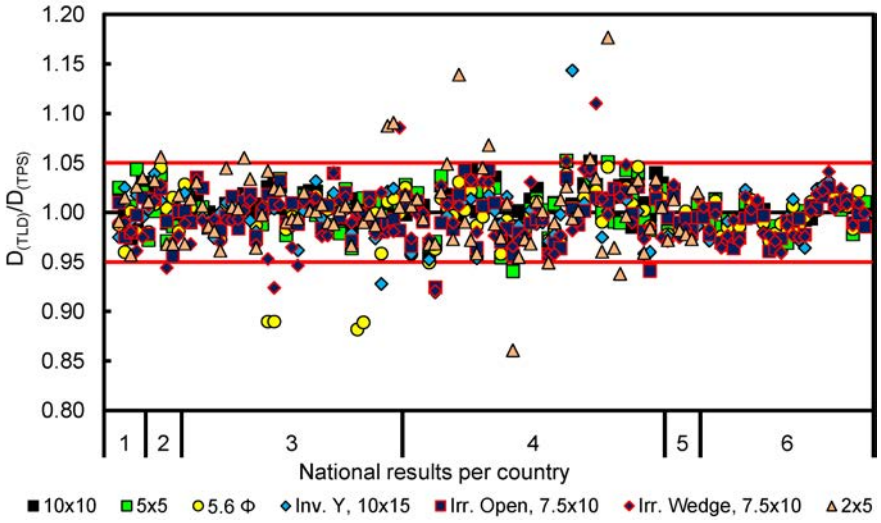


FIG. 24. Summary of $D_{(TLD)}/D_{(TPS)}$ results for seven MLC shaped fields, obtained in the respective national runs for the step 4 audit.

4.6. STEP 5: AUDITS OF COMPLEX TREATMENT PARAMETERS FOR PHOTON BEAMS; SITUATIONS INVOLVING HETEROGENEITIES

4.6.1. Introduction to the step 5 audit

The purpose of this audit is to check the heterogeneity corrected dose calculations performed by the TPS as used for patient treatments. Accurate dose calculation needs sophisticated radiation transport modelling that can account for heterogeneities in body composition [135–144]. This is particularly relevant for lungs, but also applicable to bone, in order to make optimal use of the capabilities of more complex equipment and treatments. An independent experimental verification of the heterogeneity corrected dose calculated by the TPS is an important step in the improvement of QA in radiotherapy and therefore an important extension of the DAN programme. These developments took place under CRP E2.40.16, Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques. Six DANs participated: Algeria, Argentina, Brazil, China, the Czech Republic and Poland.

4.6.2. Methodology of the step 5 audit

A specific solid phantom was developed for this audit step. The phantom cross-sectional design and configurations for use are shown in Fig. 25 (reproduced from Ref. [58]), with photos of the phantom shown in Fig. 26. Three different phantom configurations were available, involving different material compositions: polystyrene only, polystyrene plus lung equivalent material and polystyrene plus bone equivalent material. The absorbed dose to water at a 10 cm depth in the solid phantom (with and without heterogeneities) for a 6 × 6 cm^2 field was checked using TLDs. An additional TLD was located in the lung material.

The phantom had overall dimensions of 15 × 15 × 15 cm^3. In addition to the polystyrene slabs, a 15 × 15 × 5 cm^3 slab of lung equivalent material (cork) and a 15 × 15 × 2 cm^3 slab of bone equivalent material (plastic) were included. The phantom had the flexibility to be able to change the order of the various slabs to provide different configurations of polystyrene and heterogeneities. A TLD could be placed in one of the 2 cm polystyrene slabs on the central axis, while another TLD could be placed off-axis in the centre of the lung slab. This configuration ensured that the TLD measurement locations were always at least 1 cm away from any heterogeneity interface. There was also 5 cm of phantom material beyond the TLD for adequate scatter conditions.

The three solid phantom configurations (as shown in Figs 25(a)–(c)) were CT scanned using a typical clinical scan protocol. The CT scan was performed with a plug positioned in place of each TLD location.

In the TPS, the three scanned phantom configurations had a static 6 × 6 cm^2 field created and applied to the top of the phantom. The treatment field was centred on the central axis of the phantom and the phantom was positioned at 100 cm SSD. The treatment field MU values were determined so as to deliver a dose of 2 Gy at 10 cm depth on the central axis. Clinical TPS settings were used for all dose calculations. The beam energy used for this treatment field was that which was most often used clinically for treatments in the thorax region. The same energy had to be used for the bone heterogeneity test.

The phantom was then set up (sequentially for each configuration), with the plug(s) replaced with TLDs at the locations shown in Fig. 25. The treatment field was delivered to the phantom. The TLD-measured doses were compared to the absorbed dose calculations from the TPS for each of the phantom set-ups and TLD locations.

This audit tested both the TPS calculation of these configurations and the delivery of the doses to the phantom.

4.6.3. Development and testing of the step 5 audit methodology

An initial study was conducted to test the feasibility of the step 5 audit, including TLD performance as compared to IC readings. The phantom was CT imaged and the fields were planned using Oncentra MasterPlan for 6 MV and 10 MV beams. Examples of the treatment plans for (a) the polystyrene-only phantom and (b) the polystyrene and 'lung' phantom configuration are shown in Fig. 27. Five irradiation sessions were carried out on an Elekta Synergy linac, including IC measurements, as well as TLD irradiations for direct comparison. The doses at 10 cm depth in the solid phantom (with and without heterogeneities) for a 6 × 6 cm^2 field were determined. The different set-ups and points of measurement were labelled polystyrene only (P), polystyrene with bone insert (BP) and polystyrene with lung insert (LP). For the LP set-up an additional TLD was placed inside the lung equivalent material (LL). The TLDs were evaluated using the IAEA standard TLD protocol [104, 107, 133].

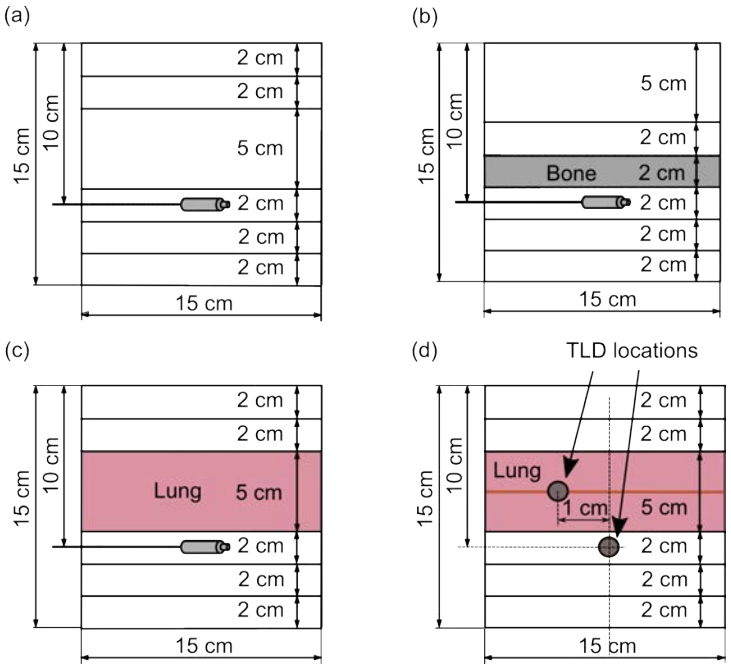


FIG. 25. Three polystyrene/heterogeneity solid phantom configurations for the quality audit of complex treatments in the presence of a heterogeneity (a)–(c); positioning of TLDs in lung-equivalent material (d) (reproduced from Ref. [58]).

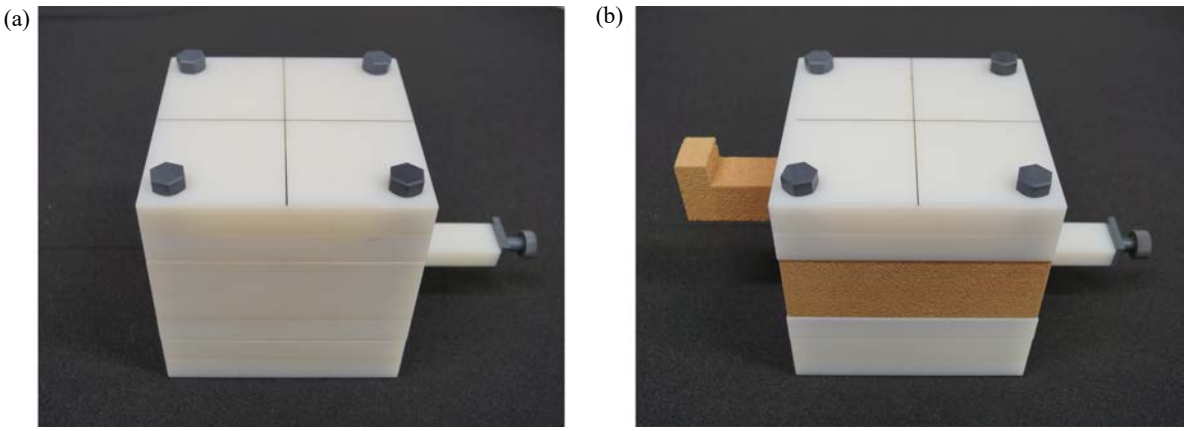


FIG. 26. Photos of the solid phantom developed within the CRP E2.40.16 for dose audits for situations involving heterogeneity. (a) The audit phantom showing the homogeneous polystyrene configuration with the TLD drawer extended; (b) the assembled phantom with lung-equivalent cork material and a TLD drawer for the additional TLD inside the lung-equivalent material.

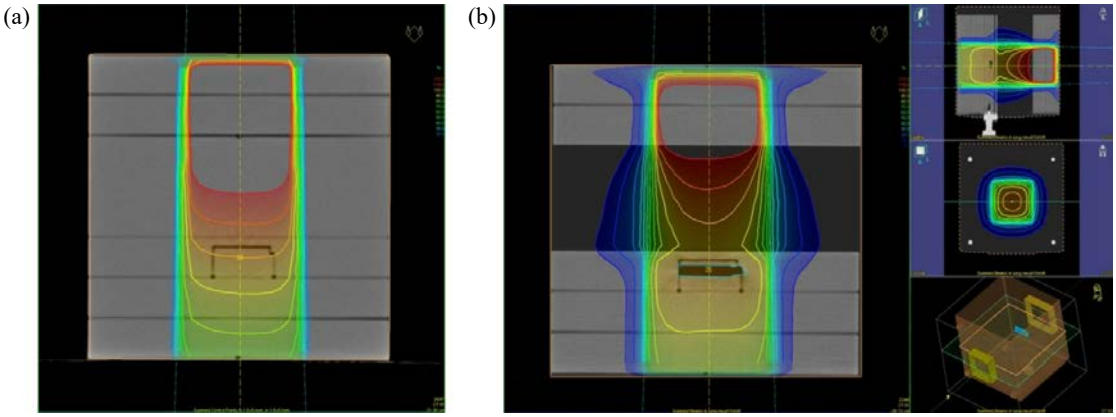


FIG. 27. Irradiation plans and resulting dose distributions obtained with the TPS Oncentra MasterPlan for two phantom configurations: (a) polystyrene-only; (b) polystyrene–lung insert.

A summary of the results from the feasibility study is provided in Table 10. The ratios of TLD doses to IC doses were all close to unity, except for the measurements directly in the lung-substitute material, where the $D_{(TLD)}/D_{(IC)}$ was measured at 1.013 and 1.014 (results not included in Table 10) for 6 MV and 10 MV respectively, providing a correction factor for the TLD capsule measurements inside the lung-substitute material.

The multicentre pilot was conducted by Algeria, Argentina, Brazil, China, the Czech Republic and Poland. Four different TPSs were used with multiple software versions and a range of different algorithms, including the pencil beam with simple heterogeneity corrections and more advanced algorithms such as AAA and collapsed cone superposition/convolution. A range of linacs from different manufacturers were used, including beam energies from 4 MV to 10 MV. Two TLDs were irradiated for each set-up.

Three participating centres carried out both TLD and IC measurements to obtain doses in the positions of the TLDs. Additionally, these centres were asked to report the electron densities obtained from the CT scanning of their phantoms for the three different materials used in the construction. These ranged from 0.94–0.98 for polystyrene, to 1.12–1.16 for the bone-substitute material and 0.21–0.28 for the lung-substitute material (cork). The correction factor between the TLD and IC measurements inside the lung insert (point LL) determined in a feasibility study was in close agreement with that determined in a multicentre pilot run. The LL corrections determined by the three centres were 1.011 (±0.001) for 6 MV and 1.015 (±0.001) for 10 MV, respectively.

TABLE 10. RATIOS OF TLD MEASURED AND TPS CALCULATED DOSES FROM THE FEASIBILITY STUDY FOR 6 MV AND 10 MV

Beam		$D_{(TLD)}/D_{(TPS)}$			
		P*	LP*	LL*	BP*
6 MV	1	0.992	0.993		0.981
	2	0.980	0.981	1.002	
	3	0.982			
	4	0.997	0.997	1.005	0.997
	5	0.985	0.995	1.004	0.972
Mean		0.987	0.991	1.004	0.984
SD_m (%)		0.3	0.4	0.1	0.7
10 MV	1	0.995	1.012		0.995
	2	0.981	0.977	0.991	
	3	0.980			
	4	1.008	0.983	0.993	0.992
	5	0.995	1.001	1.012	0.989
Mean		0.992	0.993	0.999	0.992
SD_m (%)		0.5	0.8	0.7	0.2

* P — polystyrene only, BP — polystyrene with bone insert, LP — polystyrene with lung insert, LL — LP set-up with an additional TLD placed inside the lung-equivalent material.

The ratios of TLD dose compared to TPS doses for all points, where the LL values were corrected for differences between the TLD and IC measurements for the doses inside the lung material, are summarized in Fig. 28.

As can be seen from Fig. 28, the results were consistent between participants except for centre 6. The results for centre 6 showed a systematic deviation for all measured points. This was due to an incorrect irradiation geometry; repeated irradiations by this centre resulted in improved values (see points 6(2) in Fig. 28). The mean ratios and SDs for all centres (excluding centre 6's first participation) were 0.996 ± 1.3%, 0.993 ± 1.8%, 0.990 ± 1.3 and 0.995 ± 1.2 for polystyrene, lung-polystyrene, inside lung (corrected with TLD/IC value) and for bone-polystyrene set-ups, respectively. The results show that the participants successfully completed the exercise and the ratio $D_{(TLD)}/D_{(TPS)}$ was within 3% for all phantom set-ups. The instructions and data sheets were found to be straightforward and the methodology was found to be easy to follow.

The MU required to give 2 Gy with the bone insert differed only slightly from the case with polystyrene alone (less than 2% for all centres). This was a clear indication that the amount and location of bone material used in this phantom had only a small effect on the dose at the point used. The electron density for the bone

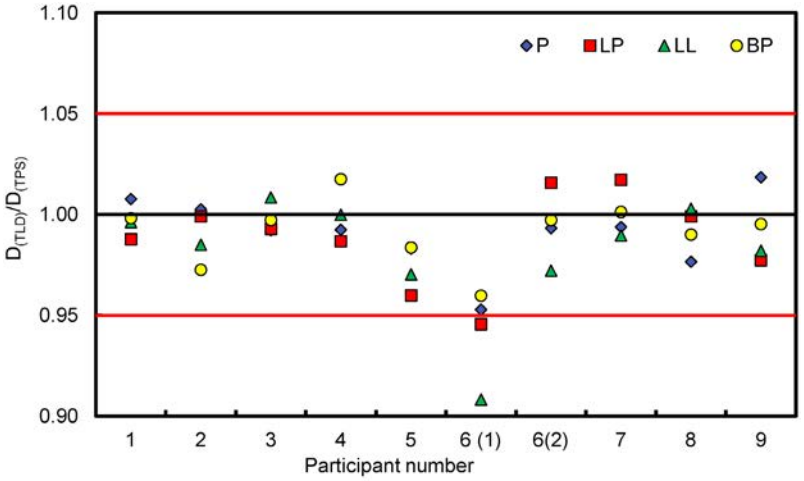


FIG. 28. Ratio of $D_{(TLD)}/D_{(TPS)}$ for all participants in the multicentre run, with LL corrected for differences between IC and TLD measurements.

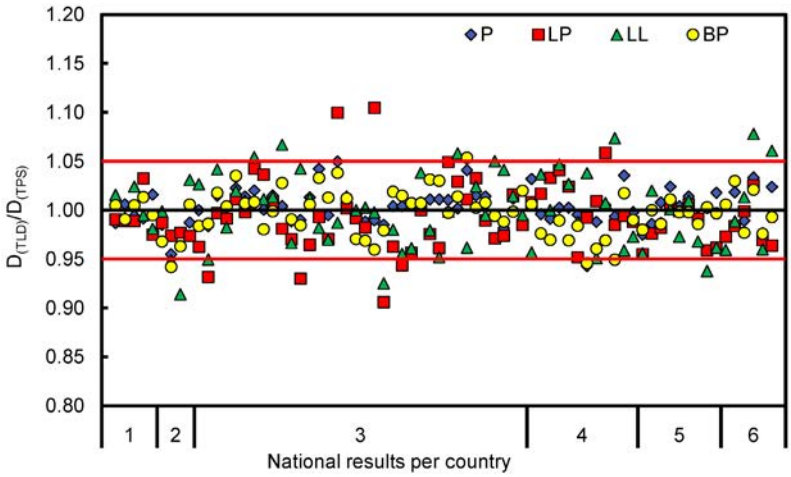


FIG. 29. Summary of the ratio of $D_{(TLD)}/D_{(TPS)}$ for all participants in the national runs.

equivalent material used in this study was on average 1.15 and is comparable to that seen in clinical practice. Although the effect is small, the DANs decided to keep this test in step 5.

Based on the results obtained in the multicentre study, the acceptance criteria between the measured and the calculated doses were established at the level of ±5% for the step 5 audit, similarly to previous audit steps.

4.6.4. Results of the national runs for the step 5 audit

Six countries (Algeria, Argentina, Brazil, China, the Czech Republic and Poland) performed the step 5 audit at a national level. In total, 72 different beams were checked, with beam energies ranging from 4 MV to 18 MV. The mean values and SDs were 1.002 ± 0.019, 0.993 ± 0.034, 0.999 ± 0.037 and 0.997 ± 0.023 for the measurement points P, LP, LL and BP, respectively. The measurement points failing the acceptance limit of ±5% were located in the lung material (LL, $N = 12$), beneath the lung material (LP, $N = 7$), beneath the bone material (BP, $N = 4$) and in polystyrene only (P, N = 1). A summary of the results of the national runs is presented in Fig. 29. Reasons for exceeding the acceptance limit for the measurement points in lung were attributed to the limitations of the dose calculation algorithms of some TPSs used in this audit.

4.6.5. Summary and conclusions for the step 5 audit

The step 5 audit methodology described in this section has been demonstrated to be feasible and practicable. It is sensitive enough to detect deviations in the TPS dose distributions, as errors caused by dose calculation algorithms with insufficient heterogeneity correction accuracy were clearly detectable. As discussed above, TPS algorithms' limitations have to be considered when comparing results from different audit participants. Not all deviations are attributable to heterogeneity algorithms; other errors can arise from incorrectly measured TPS input data, inaccuracies in the beam modelling or inaccurate CT to relative electron density conversion curves, and also from erroneous beam calibrations as well as phantom positioning errors during TLD irradiation.

The literature suggests that discrepancies in percentage depth dose curves are greater for higher energies, lower densities of heterogeneities (lung equivalent material) and smaller fields, whereas denser materials (bone equivalent material) have a smaller impact on calculations and differences [135–144]. The results of the step 5 audit are consistent with these findings.

The phantom designed for this audit step was found to be small enough to be used in postal audits, and it was generally a useful tool for auditing how TPS algorithms compute doses in the presence of heterogeneities.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 5 to specify the irradiation conditions and collect the necessary irradiation information (Package 7) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.7. STEP 6: AUDITS OF COMPLEX TREATMENT PARAMETERS: SMALL PHOTON FIELDS SHAPED BY AN MLC

4.7.1. Introduction to the step 6 audit

The purpose of this TLD and film audit was to check the dose and dose distribution profile calculations performed by the TPS for small photon MLC shaped fields as used for patient treatments. Increasingly complex treatments require more sophisticated dose measuring and modelling techniques that consider not only the magnitude of the dose, but also the shape and localization of the dose profile delivered using MLC shaped field sizes. The combination of specific TPS modelling, data input for beam modelling at commissioning and set-up in the TPS is particularly relevant for stereotactic techniques and IMRT in order to make optimal use of the capabilities of more complex equipment. An independent experimental verification using film dosimetry of the 2-D dose profiles calculated by TPSs is an important step in the improvement of QA in radiotherapy, and therefore an important extension of the DAN programme.

In step 6, the audit methodology was extended from point dose measurements with TLD to 2-D dosimetry. The 2-D dosimetry system selected was a radiochromic film, to take account of extensive experience in audits using this method and also its availability in many centres (including some of the clinical centres involved with some DANs). In addition, it could be mailed and did not need very expensive equipment or facilities for handling and readout. A small solid phantom, originally designed for the step 5 audit, was further developed to enable film dosimetry in the audit step 6, for cost effective utilization.

It needs to be highlighted that besides the usual tasks in setting up methodologies for remote quality audits, such as development of the instructions and data sheets, feasibility studies and multicentre pilot runs, it was specifically necessary for step 6 to establish radiochromic film dosimetry methodology. This methodology included film handling, positioning, irradiation, calibration and readout techniques within a DAN's MC. In this context, a special film cassette was developed and tested to hold the film.

When a national DAN had successfully implemented the step 1–4 audits, and if they had chosen to continue with photon beam complex treatment audits and develop the infrastructure and capability to perform 2-D dose distribution film analysis as their next priority, then they could proceed to the step 6 audit. This step was intended to be carried out in all hospitals for the photon energy most commonly used in the clinic (less than 12 MV) with MLC shaped fields.

These developments took place under CRP E2.40.16, Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques. The participants in the methodology development, pilot and feasibility testing and the execution of national runs for the step 6 audit were DANs from Algeria, Argentina, Brazil, China, the Czech Republic and Poland. Other participants from Austria, the UK and the USA contributed to initial development and testing of the methodology.

4.7.2. Methodology of the step 6 audit

The absorbed dose to water at a 10 cm depth in the solid phantom for a 2 × 5 cm^2 field was checked using TLDs. The 2-D dose profiles (in-plane and cross-plane) normalized to the central axis dose for 2 × 5 cm^2 and 2 × 2 cm^2 MLC shaped fields were verified using radiochromic films. All the dose calculations and measurements required in this step were carried out under SSD or SAD set-up conditions for the photon beam energy (less than 12 MV) most commonly used clinically.

The methodology development for the step 6 audit included also the design, construction and feasibility testing of a dedicated film cassette holder for the 2-D dosimetry audit based on the IAEA solid polystyrene phantom used in the step 5 audit. This phantom provided a flexible configuration to meet the requirements of this audit step and host the film, as indicated in Fig. 30.

The film analysis methodology included handling of the radiochromic film, irradiation of the film with known reference points marked on the film, scanning of the irradiated film with a flatbed scanner and creating relative dose profiles normalized to the central axis value from the measured and TPS-calculated dose values. The measured dose profiles were compared to the dose distribution determined by the TPS in the same planes of calculation as determined with the radiochromic film. The workflow process for the step 6 audit, in which the preparation of films and the film reading were performed by the Film Measurement Centre, associated with the DAN is shown in Fig. 31.

4.7.2.1. Radiochromic film preparation procedures at the Film Measurement Centre

Radiochromic film preparation procedures performed at the Film Measurement Centre were as follows:

(a) The film needed for these two measurements was to be cut from a full sheet of a radiochromic EBT film, as shown in Fig. 32. Any person handling the film was to wear cotton gloves. The film was to be stored in a black envelope until it was used. A small piece of film from the bottom of the full sheet, as indicated in Fig. 32, was to be retained for a background reading.
(b) The radiochromic film was to be positioned into the phantom film cassette, as shown in Fig. 33.
(c) The film was held in position by positioning pins located in each part of the polystyrene film cassette, as shown in Fig. 33; the pin marks on the film served to orient the film and locate the central axis on the film.
(d) Once the film was positioned within the polystyrene film cassette, the cassette and remaining polystyrene slabs were sent to the local hospital, which would carefully assemble the solid phantom prior to irradiation such that the film was located at a depth of 10 cm.
(e) The Film Measurement Centre was to determine a dose–response curve for each batch of film used in the step 6 audit.

4.7.2.2. *Dose calculation procedures at the local hospital*

Prior to irradiation of the film, the solid polystyrene phantom, as shown in Fig. 34, was assembled with no film cassette/slab present but replaced by a solid slab. It was imaged with a CT scanner and the acquired images were exported to the TPS for the subsequent dose calculation.

The dose distribution was calculated with the clinical TPS for both a 2 × 5 cm^2 and a 2 × 2 cm^2 field, shaped with the MLC at a depth of 10 cm, on the central axis of the photon beam under SSD or SAD conditions as per the clinical practice of the participating centre. Finally, dose profiles through the central axis in the in-plane and cross-plane directions were generated from the TPS calculations.

4.7.2.3. *Irradiation procedures at the local hospital*

For TLD irradiation in the solid homogeneous polystyrene phantom, 2 Gy were delivered to a TLD at a physical depth of 10 cm using a 2 × 5 cm^2 field size shaped with the MLC (Fig. 35), and the MU was

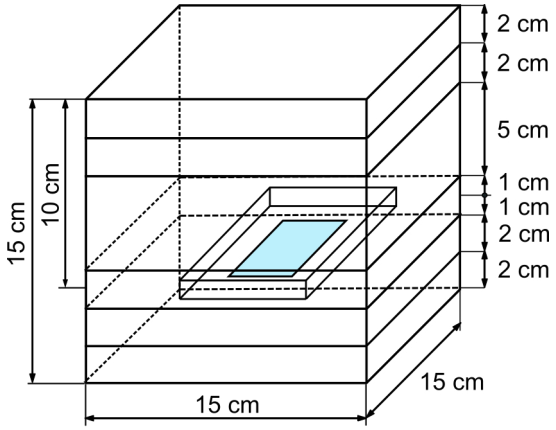


FIG. 30. Polystyrene solid phantom with film configuration for the quality audit of complex treatments.

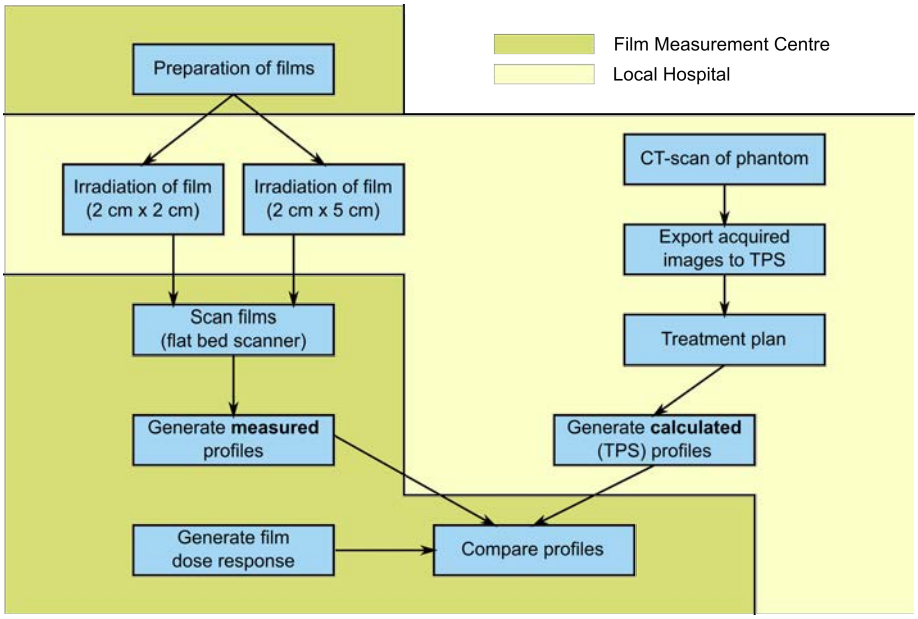


FIG. 31. The general workflow process for the 2-D dosimetry quality audit for small MLC shaped photon field sizes showing the separate responsibilities of the Film Measurement Centre and the local hospital, where the step 6 audit is performed.

calculated with the TPS according to the hospital's clinical procedure. The longitudinal axis of the TLD had to be placed parallel to the longer dimension of the MLC field.

For radiochromic film irradiation in the solid homogeneous polystyrene phantom, a dose of 8 Gy was to be delivered at a depth of 10 cm, using a 2 × 5 cm^2 field size shaped with the MLC (Fig. 36).

In the next setting, the second radiochromic film was irradiated at a depth of 10 cm with 8 Gy delivered on the beam axis according to the hospital's clinical calculation, using a 2 × 2 cm^2 field size

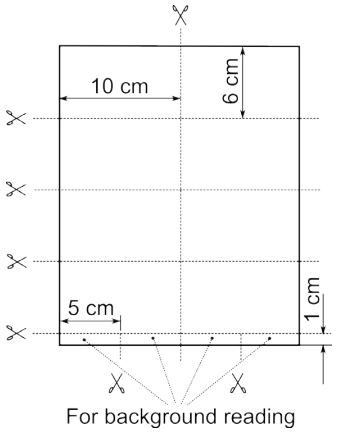


FIG. 32. The template and dimensions for cutting a full sheet of EBT radiochromic film.

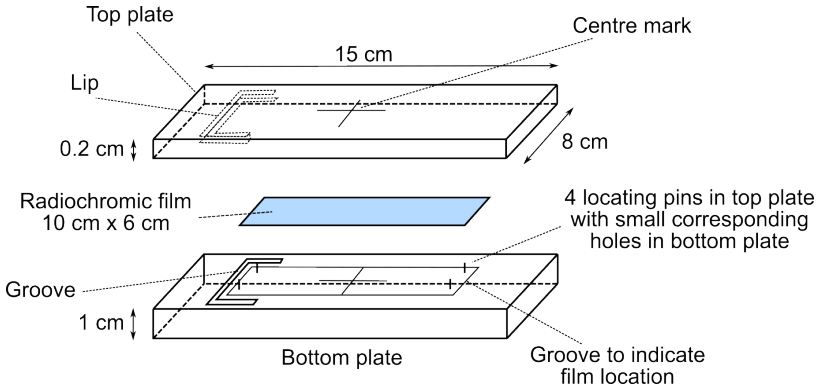


FIG. 33. The placement of the radiochromic film within the polystyrene film cassette.

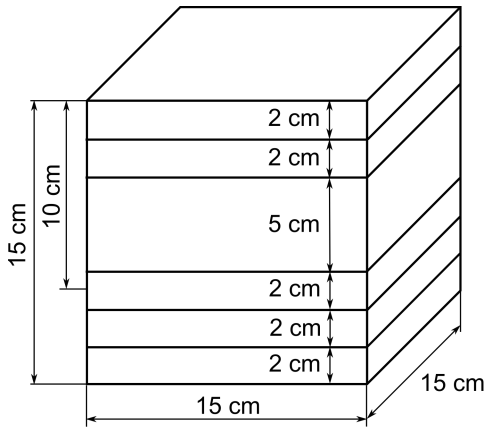


FIG. 34. Solid polystyrene phantom to be imaged without the film cassette/slab for treatment planning purposes.

shaped with the MLC (Fig. 37). After the two film irradiations had been completed, the second TLD was irradiated as specified above with the 2 × 5 cm^2 MLC shaped field.

4.7.2.4. Post-irradiation film analysis procedures at the Film Measurement Centre

The solid phantom, including the polystyrene film cassette and a background piece of radiochromic film, was returned to the Film Measurement Centre for unpacking and scanning. Any person handling the film after it had been irradiated was to wear cotton gloves and follow the recommendations for film handling (Appendix II). The film was removed from the phantom cassette and stored in a black envelope until it could be scanned. Once the film had been scanned on the flatbed scanner, the dose distribution was generated using the dose–response curve for that film batch. The profiles for the in-plane and cross-plane directions were normalized on the beam axis and compared to the dose profile calculated with the TPS at the local hospital.

4.7.3. Development and testing of the step 6 audit methodology

An initial feasibility study was conducted to test the phantom, TLD and film irradiation procedure in order to assess the step 6 audit as a whole and to provide feedback for ease of use, functionality and the quality of the instruction sheets and data forms. In a subsequent step, a multicentre pilot study was also conducted involving eight hospitals associated with the national DANs of the above mentioned participating countries.

The aim was to test and validate the newly developed methodology and audit procedures internationally, including the clarity of the technical documentation. This study also provided information regarding the practicality of mailing the solid polystyrene phantoms and cassettes with preloaded radiochromic films to other countries. The analysis of dosimeters used in the multicentre pilot studies was performed by the IAEA Dosimetry Laboratory.

Irradiations were performed by participants using 14 different beams with photon energies ranging from 4 MV to 18 MV (4 MV — one beam, 6 MV — eight beams, 10 MV — four beams, 18 MV — one beam). Films were irradiated at the IAEA Dosimetry laboratory synchronized in time with participants' irradiations. Calibration films were irradiated in the dose range of 0–9 Gy following the TRS-398 code of practice [109] for 6 MV and 10 MV beams. All films, including calibration ones, were scanned following the same protocol about 5 weeks from the date of irradiation. Analysis of the participants' films irradiated in 4 MV and 18 MV beams was performed using the calibration curves obtained from the curve for 6 MV beam by applying the scaling factors as described by Richter et al. [145]. Fitting functions for the calibration curves agreed well within the film calibration uncertainty.

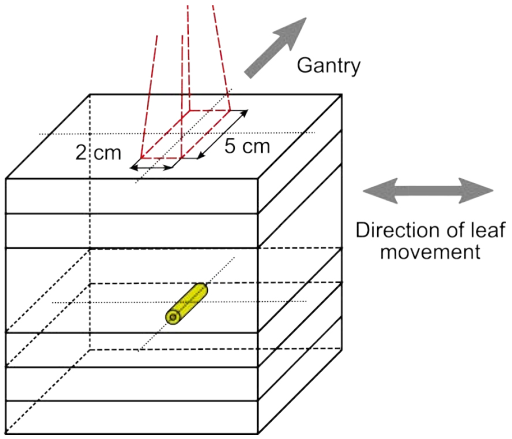


FIG. 35. The solid polystyrene phantom showing the irradiation of the TLD.

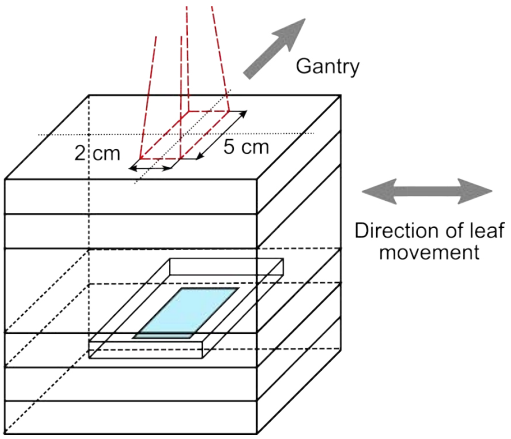


FIG. 36. The solid polystyrene phantom showing the irradiation of the film with a 2 × 5 cm^2 MLC shaped field.

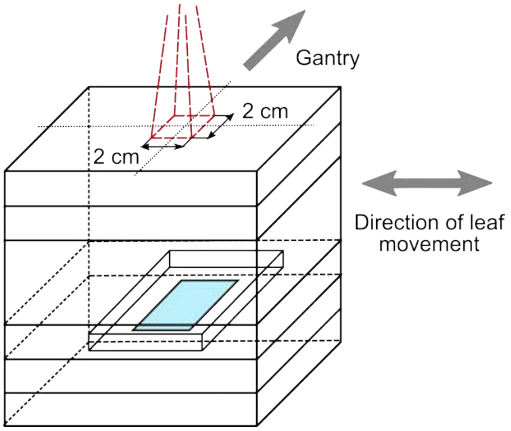


FIG. 37. The solid polystyrene phantom showing the irradiation of the film with a 2 × 2 cm^2 MLC shaped field.

Overall, 28 films received from participants were analysed. In-plane and cross-plane dose profiles (through the isocenter) were generated from all TPSs at the various hospitals with 1 mm resolution. TPS calculated and film measured profiles were superimposed and normalized at the field centre, then the differences between the profiles at the 20%, 50% and 80% dose levels were determined. A preliminary acceptance criterion of 3 mm difference between profiles at each isodose level was adopted.

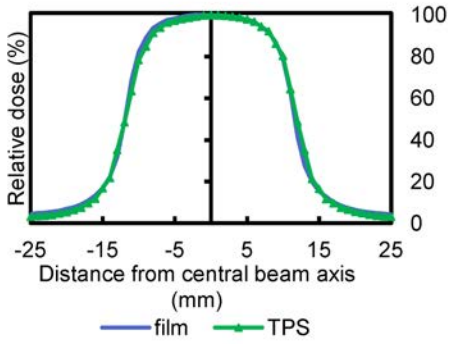
Figures 38 and 39 give representative examples of the film measurement results as compared to TPS calculations for 2 × 2 cm^2 and 2 × 5 cm^2 fields, respectively. The profile widths at the three isodose levels are also shown in tables below the respective figures. While Figs 38(a) and (b) and Figs 39(a) and (b) illustrate good agreement between the profiles, Figs 38(c) and (d) and Figs 39(c) and (d) show examples of poor results.

The differences between the profiles for both in-plane and cross-plane directions are summarized in Fig. 40. The results for the 50% isodose level were within ±2 mm for all beams, for both field sizes. On the other hand, greater discrepancies occurred for the results at the other two isodose levels, and specifically for cross-plane profiles where MLC modelling in TPS and its calibration have a greater impact on calculated and measured profiles respectively (see Fig. 40).

Three in-plane profiles and eight cross-plane profiles exceeded the 3 mm acceptance criterion at the 20% and/or 80% isodose levels. In general, most TPS cross-plane profiles that did not agree with the film measurements for 2 × 2 cm^2 fields also showed differences between the TPS and the film measurements for 2 × 5 cm^2 fields.

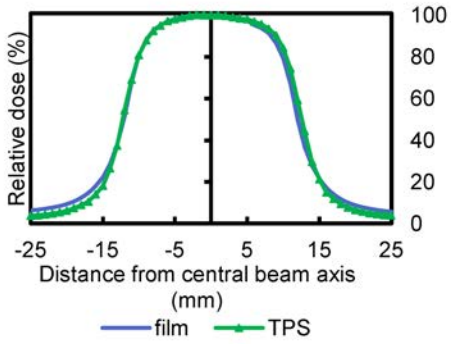
The follow-up procedures for any discrepancies all reflected existing problems with commissioning of small fields in TPS, even though all centres participated had their TPS commissioned for IMRT. This

(a)



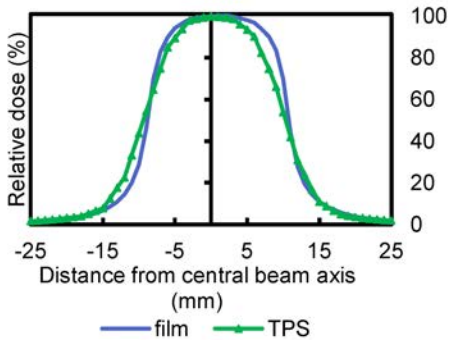
Rel. dose	TPS field size (mm) Y	Film field size (mm) Y	Film–TPS (mm)
80%	19.8	20.0	0.2
50%	**23.8**	**23.5**	**–0.3**
20%	28.6	28.4	–0.2

(b)



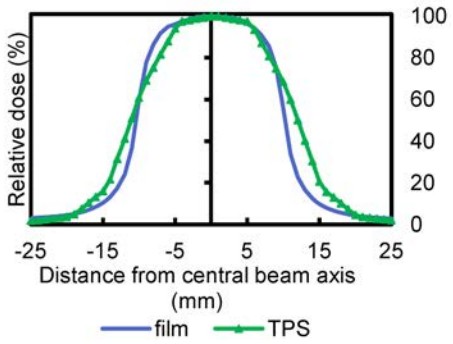
Rel. dose	TPS field size (mm) X	Film field size (mm) X	Film–TPS (mm)
80%	20.5	20.0	–0.5
50%	**24.9**	**24.1**	**–0.8**
20%	30.0	30.9	0.9

(c)



Rel. dose	TPS field size (mm) Y	Film field size (mm) Y	Film–TPS (mm)
80%	13.8	16.5	2.7
50%	**19.7**	**19.6**	**–0.1**
20%	26.1	23.9	–2.2

(d)

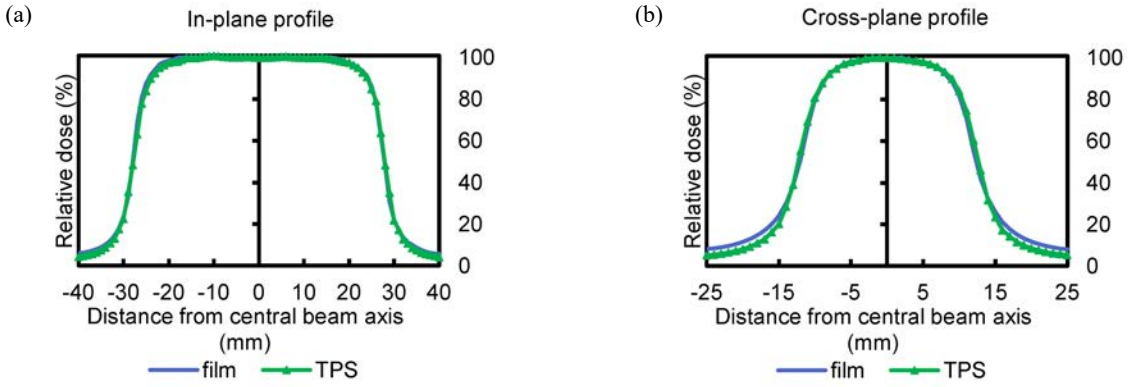


Rel. dose	TPS field size (mm) X	Film field size (mm) X	Film–TPS (mm)
80%	15.4	17.3	1.9
50%	**23.1**	**20.7**	**–2.4**
20%	29.4	25.0	–4.4

FIG. 38. Examples of results of comparisons between TPS and film profiles for high-energy photon beam, 2×2 cm^2 field size:(a) and (b) — good agreement; (c) and (d) — poor agreement.

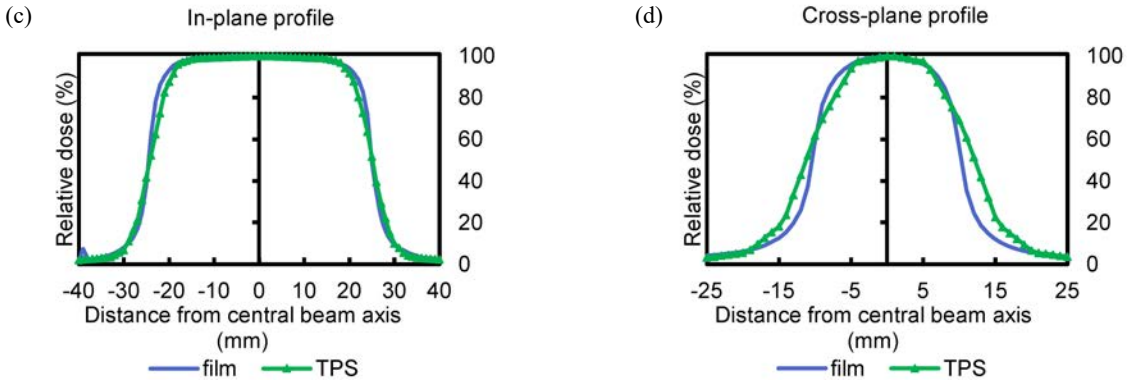
reflected the fact that the detector choice for the TPS commissioning at the centres where deviations were noted had a big impact on beam modelling [58, 146].

According to the methodology, the TPS calculated and film measured doses were additionally verified with TLDs for the 2 × 5 cm^2 field size at a 10 cm depth in a solid water phantom. The field dimensions were found to be adequate for the standard IAEA TLD capsule. The participants were asked to perform the audit using two beams of energies less than 12 MV; some participants performed the audit with two different TPSs for the same energy. The TLD results are summarized in Fig. 41. The ratios of the TLD-measured doses against the TPS-calculated doses ($D_{(TLD)}/D_{(TPS)}$) were all but one within 5% acceptance limits, with the majority of results (11/14) falling within 3%.



Rel. dose	TPS field size (mm) Y	Film field size (mm) Y	Film–TPS (mm)
80%	51.5	51.9	51.9
50%	**55.8**	**55.8**	**0.0**
20%	60.9	61.1	0.2

Rel. dose	TPS field size (mm) X	Film field size (mm) X	Film–TPS (mm)
80%	20.5	20.1	–0.4
50%	**25.0**	**24.5**	**–0.5**
20%	30.6	32.4	1.8



Rel. dose	TPS field size (mm) Y	Film field size (mm) Y	Film–TPS (mm)
80%	43.3	46.0	2.7
50%	**49.3**	**49.5**	**0.1**
20%	55.5	54.0	–1.5

Rel. dose	TPS field size (mm) X	Film field size (mm) X	Film–TPS (mm)
80%	15.6	17.1	1.5
50%	**23.4**	**20.7**	**–2.7**
20%	30.2	25.7	–4.5

FIG. 39. Results of comparisons between TPS and film profiles for high-energy photon beam, 2×5 cm² field size: (a) and (b) — good agreement; (c) and (d) — poor agreement.

4.7.4. Results of the national runs for the step 6 audit

The national trial run results were provided by Brazil, China and Poland. The results of comparisons between the film-measured and TPS-calculated in-plane and cross-plane beam profiles for 2 × 2 cm² and 2 × 5 cm² fields are shown in Fig. 42. The participants used mostly 6 MV beams, but 10 MV was also used. The TPSs used for dose calculations were iPlan, Eclipse, XiO/CMS, OMP, Monaco and Precise Plan. As can be seen in Fig. 42, there were similarities in the results between the national trial runs and the multicentre study.

Good agreement between the TPS-calculated profiles and the film-measured profiles was achieved at the 50% isodose level, with the differences not exceeding 3 mm for all but one participant, whereas for 20% and 80% dose levels the results were more scattered, with a few deviations up to 11.7 mm for 2 × 5 cm² fields. In contrast to the results of the multicentre pilot study, in the national trial run data sets, there was no clear difference between the number of deviations outside the acceptance limit of

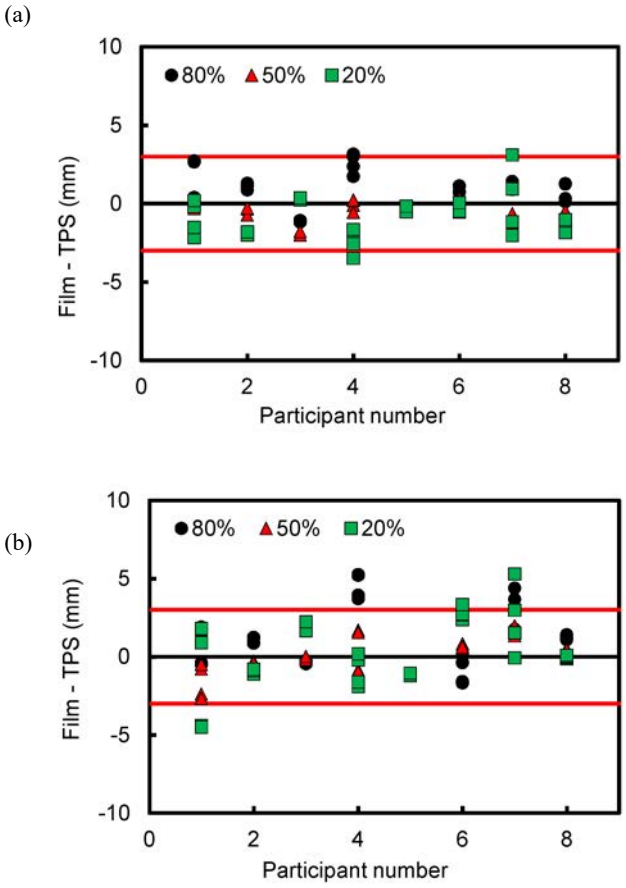


FIG. 40. The differences between the measured and calculated beam profile widths in-plane (a) and cross-plane (b) for 2 × 2 cm² and 2 × 5 cm² field sizes.

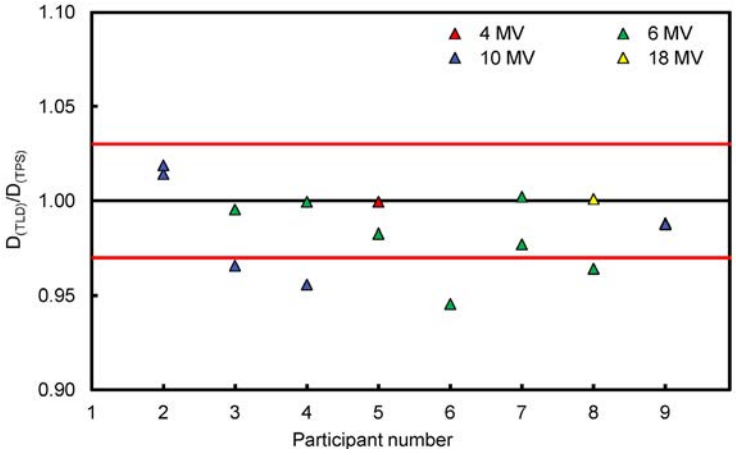


FIG. 41. Participants' results for absorbed dose to water at 10 cm depth in a solid water phantom for a 2 × 5 cm² field size for TLD irradiated to 2 Gy.

±3 mm for in-plane and cross-plane profiles. Any such deviations were communicated to the participating radiotherapy centres and followed up at the national level.

The results of the TLD audits for 2 × 5 cm² fields are summarized in Fig. 43. All TLD results but one were within the 5% acceptance limit. The discrepancy between the TLD-determined dose and the

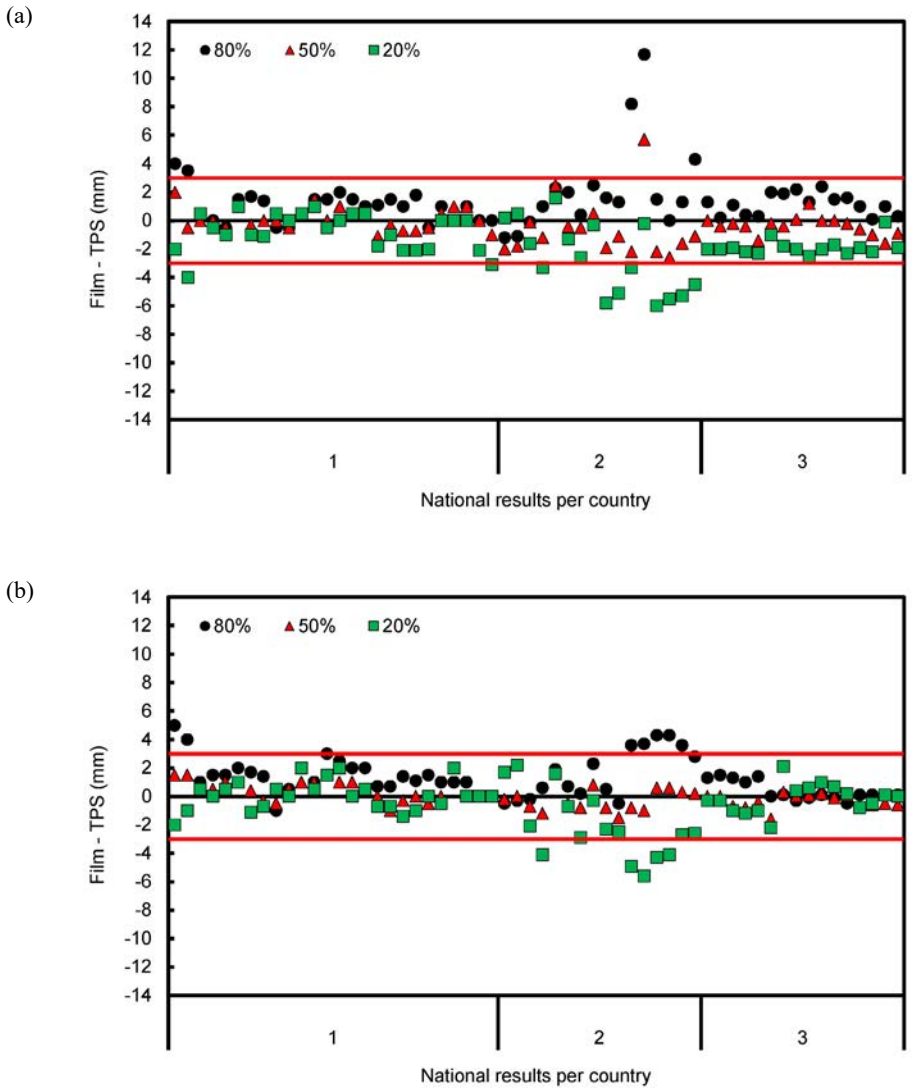


FIG. 42. The differences between the measured and calculated beam profile widths in-plane (a) and cross-plane (b) for 2 × 2 cm² and 2 × 5 cm² field sizes.

dose calculated by the TPS may indicate a problem with TPS commissioning for small beams in the centre involved.

Similarly to the multicentre pilot run, on average the TLD-determined dose was lower than the TPS-calculated dose, which might be attributed to the overestimation of small beam output factors by TPSs or the uncertainties in the TLD positioning for irradiation.

4.7.5. Summary and conclusions for the step 6 audit

The results of the multicentre pilot study indicated that the auditing procedures were adequate for detecting various issues related to small field modelling in TPS, which is important for IMRT or stereotactic treatments. The phantom was found suitable for postal audits.

Procedures developed for remote radiochromic film dosimetry were found feasible. The link between a national DAN and a national Film Measurement Centre, which are not necessarily identical, could be established in all participating countries. As such, the step 6 audit involved an important extension of dosimetry methods towards 2-D dosimetry, which was essential for steps 7, 8 and 9 for remote audits of advanced treatment techniques.

The key finding was that if a good agreement at the 50% isodose levels between the measured and TPS-calculated dose profiles was obtained, one could not conclude that the rest of the profile (e.g. 20% and 80% isodose levels) was in good agreement as well. It is particularly the case for cross-plane profiles which are shaped by MLC; modelling of leaf ends in TPS, sub-optimal small field commissioning in TPS or MLC positioning uncertainty might be the reasons for that. The results of this study demonstrated that adopting the acceptance limits of ±3 mm for the three isodose levels at the national level might be challenging in some countries.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 6 to specify the irradiation conditions and collect the necessary irradiation information (Package 8) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.8. STEP 7A: QUALITY AUDITS OF OUTPUT FACTORS OF SMALL FIELDS SHAPED WITH MLC

4.8.1. Introduction to the step 7a audit

The methodology for quality audits for dose dependence of small fields shaped with MLC was developed within CRP E2.40.18, Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery, which covered the initial essential stages for such advanced treatments. The national DANs involved as participants in this CRP were those of Algeria, Brazil, China, the Czech Republic, India, Poland and Thailand. Other participants from Austria, Belgium, Finland, Sweden, the UK and the United States of America (USA) contributed to the initial development and testing of the methodology. The aim of step 7a was to evaluate the dosimetric performance of the TPS generation of output factors for small fields. To optimize effort for participating institutions and rapid implementation in the participating countries, these generated output factors were compared to an existing published standard data set for small field size output factors [147–150]. These small field size output factor checks are necessary to identify and correct potential deviations in the calculation of absorbed doses for small segments in the delivery of IMRT or VMAT, as well as stereotactic radiotherapy techniques (i.e. SBRT, stereotactic ablative radiation therapy, SRS or stereotactic radiotherapy for cranial applications). It was intended that this quality audit step be carried out by all hospitals, for those photon beams used clinically for IMRT/VMAT and stereotactic treatment techniques.

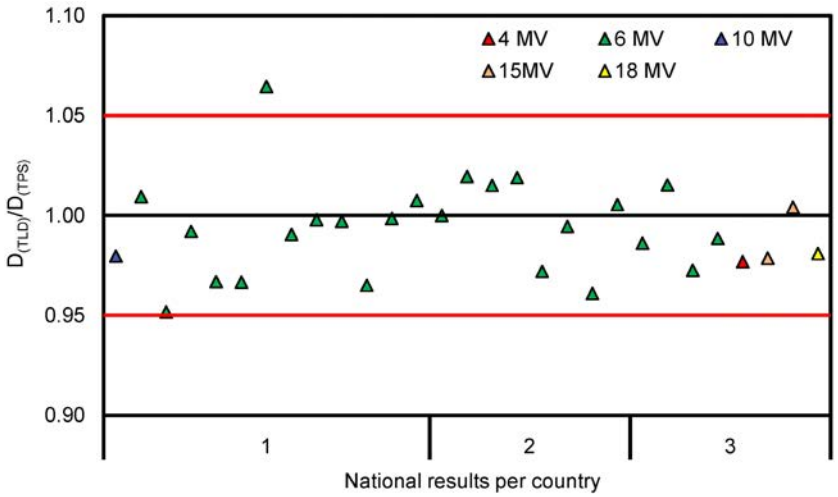


FIG. 43. National trial run results for the absorbed dose to water for TLD irradiated in a 2 × 5 cm^2 beam at a 10 cm depth in a solid water phantom.

4.8.2. Methodology of the step 7a audit

The absorbed dose rate to water at 10 cm depth for four MLC defined small fields (6 × 6 cm^2, 4 × 4 cm^2, 3 × 3 cm^2 and 2 × 2 cm^2), normalized to a reference 10 × 10 cm^2 field, was checked against published reference dose output factors [147–150].

The number of MU required to deliver 10 Gy was calculated to a point at 10 cm depth in a 30 × 30 × 30 cm^3 water phantom, on the central axis, at 100 cm SSD. For Elekta and Siemens accelerators, this was done for each field size set symmetrically about the central axis with the jaw and MLC (10 × 10 cm^2, 6 × 6 cm^2, 4 × 4 cm^2, 3 × 3 cm^2 and 2 × 2 cm^2). For Varian accelerators, the field sizes were defined by the MLC while the secondary jaws were left fixed at a field size of 10 × 10 cm^2 (Fig. 44). These calculations were repeated for each photon beam energy used for IMRT treatments. The results were sent to the DAN for analysis and comparison with the published data.

The number of MU required to deliver 10 Gy using the reference 10 × 10 cm^2 field relative to the number of MU required to deliver 10 Gy in the small field defines the small field output factor.

4.8.3. Development and testing of the step 7a audit methodology

As a first step, initial validation of the reference data was conducted by measurements (i.e. small field output factors were measured by consultants from Austria, Belgium, Finland and the UK) generating 21 data sets. The reference data sets were examined by comparing measured values from the consultants to these reference values. Overall, good agreement was found between these values, as shown in Fig. 45. The data shown in Table 11 indicate that the average of all of the measured to reference data ratios was near unity and the SDs ranged from 1.2% to 0.9%.

Based on good agreement between the reference data and measurements by the CRP consultants, the TPS-calculated output factors were compared to the reference data sets for an expanded cohort of beams. This was done in the multicentre pilot study by a total of 17 institutions from Algeria, Austria, Belgium, Brazil, China, Cuba, the Czech Republic, Finland, India, Poland, Sweden, Thailand, the UK and the USA, which generated 35 data sets (133 data points) from seven different TPSs (Eclipse, Pinnacle, XiO, iPlan, PrecisePlan, Oncentra and Monaco). The data sets were computed for three linac manufacturers, Elekta, Siemens and Varian, for different linac models, although many of these models are dosimetrically equivalent [147–150].

The comparison of TPS-generated output factor data versus the published reference data sets is shown in Fig. 46. Substantial variability was seen in the calculation of these small field output factors. The mean value for 2 × 2 cm^2 fields was 1.025 with an SD of 2.3%; for the 3 × 3 cm^2 field it was 1.014 with an SD of 1.1% (Table 12).

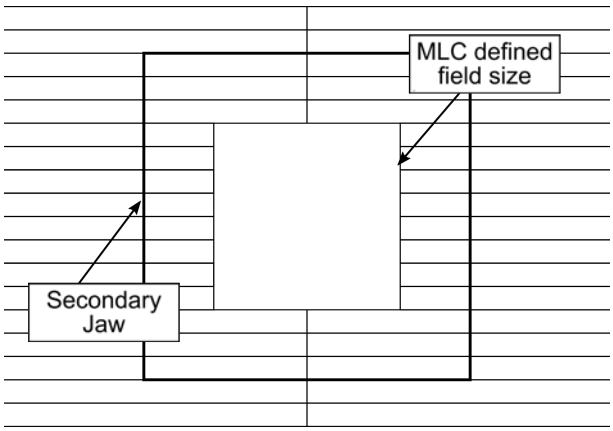


FIG. 44. Field size as defined for Varian accelerators. The secondary jaws define a 10 × 10 cm^2 field, while the MLC defines the segment size.

Given the results of the multicentre pilot study, preliminary acceptance criteria of ±2% for fields down to 3 × 3 cm^2 and ±3% separately for the 2 × 2 cm^2 field were adopted because of the high degree of variation observed in dose calculations for these fields, which was a result of the higher degree of uncertainty in the IC commissioning measurements for this field size. However, this audit is based on comparison to the published reference data and not to the measurement; therefore, any results that are not in agreement with the reference data require follow-up with measurements before an error can be confirmed.

The majority (110 of 133) of the TPS-generated data points, as seen in Fig. 46, agreed with the reference data set within the acceptance criteria for the corresponding field size. Fourteen of the 35 data sets had one or more data points that fell outside the acceptance criteria. One data set showed a disagreement with the reference data set in excess of 10% for the 2 × 2 cm^2 field.

4.8.4. Results of the national runs for the step 7a audit

Once the methodology had been tested, it was implemented within a national framework by five DANs (Brazil, China, the Czech Republic, India and Poland) [151–153]. Details on national participation in step 7a are shown in Table 13. A total of 114 institutions participated in the national audit programmes, and they contributed 186 data sets for comparison against reference data. Data sets were submitted from all three major linac manufacturers (Varian, Elekta and Siemens) and for photon beam energies ranging from 6 MV to 20 MV.

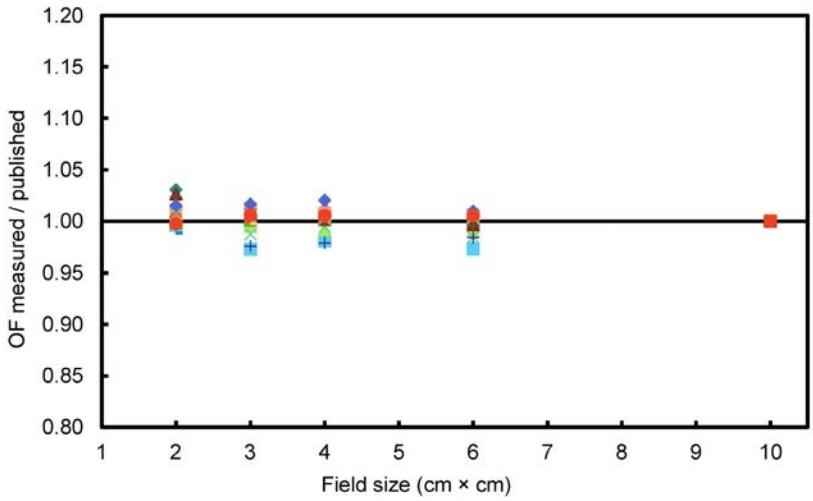


FIG. 45. Ratios of measured to reference output factors (OF) showing that the reference data agreed well with measurement. The different symbols represent the data of individual participants.

TABLE 11. THE MEAN AND SD OF THE RATIOS OF MEASURED TO REFERENCE OUTPUT FACTORS BY THE MULTICENTRE PARTICIPATING INSTITUTIONS FOR ALL MEASURED DATA SETS

	Field size (cm^2)			
	2 × 2	3 × 3	4 × 4	6 × 6
Mean	1.006	1.002	1.002	0.998
SD	0.011	0.012	0.010	0.009

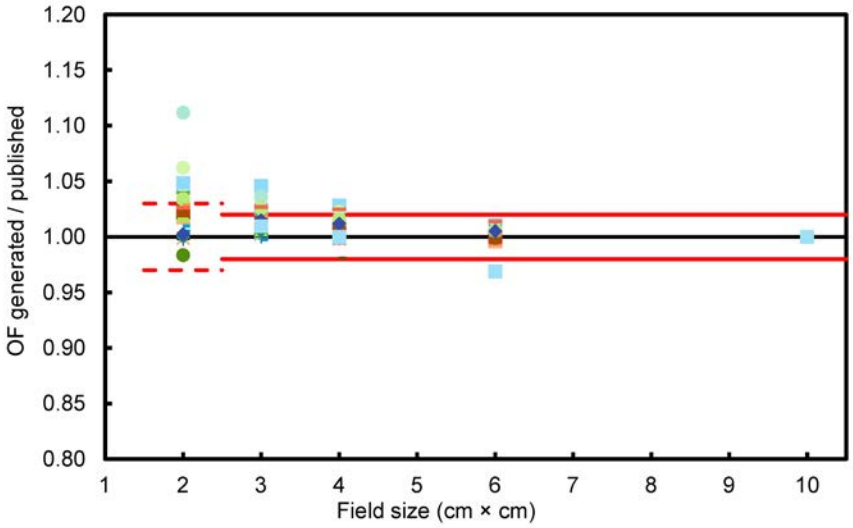


FIG. 46. Ratios of TPS-generated output factors (OF) to reference data set output factors in the multicentre pilot study. The different symbols represent the data of individual participants.

TABLE 12. THE MEAN, SD AND RANGE OF THE RATIOS OF THE TPS-GENERATED OUTPUT FACTORS TO REFERENCE OUTPUT FACTORS IN THE MULTICENTRE PILOT STUDY

	Field size (cm^2)			
	2 × 2	3 × 3	4 × 4	6 × 6
Mean	1.025	1.014	1.008	1.001
SD	0.023	0.011	0.009	0.007
Range	[0.984, 1.112]	[0.998, 1.046]	[0.981, 1.028]	[0.996, 1.014]

The average ratios and SDs between the TPS-generated output factors and the reference output factors during the national audit runs are shown in Fig. 47. These results, divided by participating country and including statistical descriptions, are summarized in Table 14. Similar to the multicentre study, the national audit runs showed that, in general, TPSs overestimate the dose for small fields, especially for the 2 × 2 cm^2 and 3 × 3 cm^2 field sizes. A large number of institutions' calculated output factors were not within the established action levels; 30% of 2 × 2 cm^2 field size data points did not agree, while for 3 × 3 cm^2 or larger field sizes only 14% of data points fell outside the action levels.

Country 3 had a very pronounced rate of substantial deviations from the reference data set. For this country, 57% of the 2 × 2 cm^2 data points did not meet the 3% action level and many results were more than 10% different. This problem was attributed to a systematic issue in the commissioning process of Varian data. A common set of vendor-supplied small field output factors was widely distributed and used throughout this country; unfortunately, these values were not correct. This reflects the importance of small field measurements and small field beam modelling, which should be based on a thorough understanding of the model and what data values to incorporate into the model (and particularly, not using so-called 'golden data sets' that might not adequately describe appropriate small field data). In contrast, country 4 produced audit results that showed a mean that was very close to unity, as well as a relatively small SD. This was done with a distribution of linac manufacturers comparable to other countries. The

results from country 4, which were comparable to the results of the multicentre pilot run, indicate the possibility to achieve good results in clinical practice in these situations, and hence in such an audit.

The high failure rate for the 2 × 2 cm^2 field size in the national audit runs indicates two current challenges within the radiotherapy community. The first is using the correct dosimetry equipment, small volume dose measurement devices, to make the appropriate output factor measurements for smaller fields. It was found that some institutions had used larger volume ICs, which are known to give low signals due to volume averaging effects in very small fields [121, 128, 146]. These incorrect data were then used to model the treatment beams in the TPSs. The second issue involves understanding the beam modelling procedure in detail of each institution's TPS to ensure appropriate dose calculation for small fields. There have been publications to assist medical physicists to model small fields for specific TPSs [147–150, 154].

An analysis of the TPS-generated output factors to reference data set factors as a function of treatment energy is shown in Table 15. The mean values for 6 and 18 MV for the 2 × 2 cm^2 field size are greater than those seen for the other energies. This elevated ratio at 6 MV is consistent with previous findings (i.e. in the original reference data set evaluation [147]), whereas the elevated ratio at 18 MV is not, as the original reference data set found generally good TPS calculation agreement at high energies. In this study, the high ratio at 18 MV is a result of the data distribution: 12 out of the 14 data sets at 18 MV were submitted by country 3, which, as described above, had systematic errors in its small field output factors.

An analysis of the calculated output factors to reference output factor ratios by linac vendor is shown in Table 16. The numbers of data sets are the greatest for Varian users, followed by Elekta and Siemens users. The mean value for the calculated-to-reference output factor ratios for the 2 × 2 cm^2 field size is 1.030 for Varian users and 1.016 for Siemens users, with SDs of 3.1% and 4.8%, respectively. The results of Elekta users were the closest to unity for the majority of field sizes, and the greatest fraction of their results were within the action levels. This is most likely attributable to the specifics of the commissioning process for TPSs commonly used with Elekta linacs.

Eighteen participants in the national audit runs also conducted independent measurements of the output factors as a follow-up to the audit. Eight of these follow-up results were for initial audit results outside of the acceptance criteria. When these output factors were directly measured as a follow-up check, the measured output factors were closer to the reference values than the TPS-generated values in 16 of the

TABLE 13. NATIONAL AUDIT STUDY PARTICIPANT DEMOGRAPHICS

Country	Number of institutions	Number of TPSs*	Accelerator models			
			Varian	Siemens	Elekta	Energies (MV)
Brazil	15	4	18	0	2	6, 10
China	27	6	15	2	3	6
Czech Rep.	14	5	16	1	2	6, 10, 18
India	30	7	18	1	1	6, 10, 15
Poland	28	6	33	2	2	6, 10, 15, 18, 20
Total	114	9	100	6	10	

* This value indicates the number of distinct TPSs from which data sets were generated.

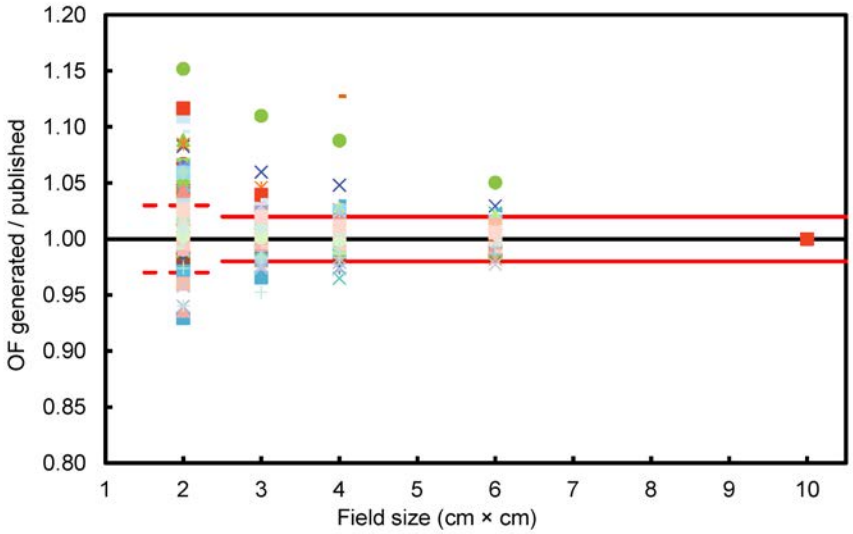


FIG. 47. The TPS-calculated versus reference output factors (OF) for small fields from all countries in the national audit runs. The different symbols represent the data of individual participants.

TABLE 14. THE MEAN, SD AND PERCENTAGE OF DATA POINTS OUTSIDE OF THE ACTION LEVEL CRITERIA FOR ALL FIELD SIZES AS PART OF THE NATIONAL AUDIT RUN

Country	Number of data sets	Field size (cm^2)		% of 2 × 2 data points outside of 3%	Field size (cm^2)						% of 3 × 3 to 6 × 6 data points outside of 2%
		2 × 2			3 × 3		4 × 4		6 × 6		
		Mean	SD		Mean	SD	Mean	SD	Mean	SD	
Country 1	22	1.020	0.020	27%	1.016	0.010	1.009	0.007	1.002	0.004	12%
Country 2	30	1.019	0.035	23%	1.012	0.025	1.009	0.020	1.003	0.014	21%
Country 3	28	1.039	0.051	57%	1.016	0.023	1.007	0.013	1.001	0.008	30%
Country 4	30	1.006	0.023	12%	1.006	0.014	1.001	0.012	0.998	0.007	9%
Country 5	76	1.016	0.028	30%	1.009	0.013	1.004	0.010	1.001	0.007	8%
Total	186	1.020	0.031	30%	1.012	0.017	1.006	0.012	1.001	0.008	16%

Note: Two more countries entered three centres into the multicentre study, so their results contribute to that analysis.

18 cases (and all eight of the cases that were out of tolerance). The measured results are summarized in Table 17. This finding supports this audit being based on a reference data set.

4.8.5. Summary and conclusions for the step 7a audit

The results of the multicentre study and the subsequent national audit runs confirmed two things: first, that this audit step has relevance for achieving the highest possible dosimetric accuracy for field sizes below 4 × 4 cm^2, and second, that the design of the auditing procedures was adequate. About 30% of the data sets were outside the action level for at least one field size. A major component of this was the overall trend that the TPS-calculated doses were higher than those actually generated by the linac. However, other issues introduced substantial errors in excess of 10% in the calculated output factor. A major systematic error was observed when incorrect, manufacturer-supplied, standard data were input into TPSs. Errors were also attributed to the measurement methods for small fields; there were several cases noted of ICs being used with volumes that were inappropriately large, such as a 0.6 cc chamber

TABLE 15. THE MEAN AND SD FOR ALL FIELD SIZES ANALYSED BY BEAM ENERGY

Beam energy	Number of data sets	Field size (cm^2)							
		2 × 2		3 × 3		4 × 4		6 × 6	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
6 MV	133	1.020	0.028	1.012	0.017	1.007	0.018	1.001	0.009
10 MV	8	1.011	0.011	1.014	0.004	1.007	0.004	1.000	0.004
15 MV	24	1.000	0.027	1.001	0.011	1.000	0.007	1.002	0.004
18 MV	14	1.050	0.066	1.014	0.027	1.002	0.011	0.999	0.008
20 MV	3	1.015	0.010	1.013	0.006	1.008	0.003	1.005	0.001
Total	186	1.019	0.033	1.011	0.017	1.006	0.016	1.001	0.008

TABLE 16. THE MEAN, SD AND PERCENTAGE OF DATA POINTS OUTSIDE OF THE ACCEPTANCE CRITERIA FOR ALL FIELD SIZES ANALYSED FOR USERS OF DIFFERENT LINACS

Linac vendor	Number of data sets	Field size (cm^2) 2 × 2 Mean	Field size (cm^2) 2 × 2 SD	% of 2 × 2 data points outside of 3%	Field size (cm^2) 3 × 3 Mean	Field size (cm^2) 3 × 3 SD	Field size (cm^2) 4 × 4 Mean	Field size (cm^2) 4 × 4 SD	Field size (cm^2) 6 × 6 Mean	Field size (cm^2) 6 × 6 SD	% of 3 × 3 to 6 × 6 data points outside of 2%
		TPS-generated output factor to the reference output factor ratio									
Elekta	57	1.003	0.019	13%	1.000	0.011	0.996	0.008	0.995	0.006	4%
Siemens	29	1.016	0.048	48%	1.011	0.027	1.014	0.030	1.007	0.012	21%
Varian	100	1.030	0.031	35%	1.017	0.013	1.011	0.012	1.003	0.005	18%

for a 2 × 2 cm^2 field. The consequences of using inappropriate detectors for making small field dose measurements have been previously reported [121, 128, 155, 156].

Due to the magnitude of deviations in small field results and the nature of these errors, national audit groups need to recommend that clinics commission their TPSs, and any other dosimetric systems, in accordance with the clinical guidelines available. This includes careful measurement of the required parameters (output factors, profiles, etc.) and comparison with relevant reference data sets [147–150] where available; selection of appropriate data to optimize the TPS model for small fields (i.e. data covering small field sizes of interest); and comprehensive validation and verification of the model performance against measurement before clinical use [157]. This should be based on a clear understanding by the local medical physicist of the dosimetry of small fields and of the small field beam characteristics of the linacs in use locally, as well as of small field modelling in the specific TPS being used (including leaf end modelling, dosimetric leaf gap or equivalent, etc). The latter requires specific training for the TPS in use and also after any change in version, algorithm or other feature.

Note that errors and uncertainties in small field dosimetry and treatment planning will impact on IMRT and VMAT dose distribution, where small segments are an intrinsic part of treatment delivery. The impact will vary with the complexity of treatment. In addition, these same small field errors and uncertainties noted above will impact directly on small field treatments, such as those used in stereotactic delivery methods.

A major strength of this audit is the ease of its implementation. A great number of institutions participated in this audit, in large part because of its simplicity; completing this audit required no additional equipment and took less than 1 hour. A limitation of this audit is that reference data has to exist in order for it to be conducted. At the time of the national audit runs, eight flattening filter free data sets could not be analysed because of a lack of reference data. Fortunately, subsequent data on additional beams (including flattening filter free beams) has been published [149]. An additional limitation is that the TPS calculations are compared to reference data and not measurement; because of that, results that are not in agreement require follow-up before confirmation of an error is possible.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 7a to specify the irradiation conditions and collect the necessary irradiation information (Package 9) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

TABLE 17. RESULTS OF FOLLOW-UP MEASUREMENTS OF SMALL FIELD OUTPUT FACTORS BY PARTICIPANTS IN THE NATIONAL AUDIT STUDY. THE MEAN AND SD FOR EACH FIELD SIZE IS SHOWN FOR THE RATIO OF MEASURED OUTPUT TO REFERENCE OUTPUT

Linac	Number of data sets	Field size (cm^2)							
		2 × 2		3 × 3		4 × 4		6 × 6	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Elekta	6	1.001	0.015	1.001	0.008	0.999	0.007	0.997	0.004
Siemens	2	1.013	0.018	1.013	0.004	1.008	0.001	1.004	0.001
Varian	10	1.016	0.013	1.007	0.013	1.009	0.010	1.003	0.006

4.9. STEP 7B: FILM QUALITY AUDIT OF MLC PERFORMANCE FOR IMRT DOSE DELIVERY

4.9.1. Introduction to the step 7b audit

The methodology for the step 7b audit checking the MLC performance for IMRT dose delivery was developed within CRP E2.40.18, Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery. The national DANs participating in this CRP step were those of Algeria, Brazil, China, the Czech Republic, India, Poland and Thailand. Other participants from Austria, Belgium, Finland, Sweden, the UK and the USA contributed to the initial development and testing of the methodology.

The aim of step 7b was to assess a 'picket fence' test as an audit tool for verifying the positioning accuracy of MLC leaves [158]. The MLC performance is a critical component of IMRT delivery, particularly because its positioning accuracy directly influences the dosimetry and position, and hence overall quality, of treatment. Increasingly, advanced technology treatments such as IMRT and VMAT employ steep dose gradients between treatment targets and adjacent organs at risk that require not only the magnitude of the dose to be accurate, but also the shape of the dose distribution, including the position and edges of the field. All of these may only be achieved with accurate MLC positioning. This was tested in this audit step by irradiating a sheet of radiochromic film with an MLC pattern consisting of five parallel strips. The actual positions of these strips were compared to the predicted ones to verify the MLC performance. In addition, the consistency of the width of the MLC strips was checked as a test of each leaf's positioning accuracy.

4.9.2. Methodology of the step 7b audit

An image of a five-strip picket fence pattern used in this audit step is shown in Fig. 48. Participants were asked to create each of five MLC strips with a minimum (not less than 5 mm) width achievable with their MLC. The nominal centre of each strip was separated by 3 cm from the next, with MLC strip positions at –6 cm, –3 cm, 0 cm, 3 cm and 6 cm relative to the central axis. For Varian machines, the central strip was defined by the secondary jaws, while the outer strips were defined by the MLC with the secondary jaws in the cross-plane direction retracted so as not to obscure the MLC field. The jaws in the in-plane direction were opened to the maximum field size. For Elekta machines, the backup jaws in the cross-plane direction were retracted completely.

Radiochromic film was used to measure the delivered dose distribution. The film was sandwiched between solid slabs, as shown in Fig. 49. Typically, not all leaf pairs can be captured on the film; the central leaf pairs need to be aligned near the centre of the film to capture maximum information. The film plane was located at 100 cm SAD at a depth approximately equal to d_{max}. The film was irradiated using 250 MU per strip. The strip positions measured on the films were defined relative to the middle strip, whereas the middle strip (i.e. the jaws for Varian accelerators or simply the middle MLC strip for Elekta and Siemens accelerators) was defined to be at the zero position (0 mm).

The strip pattern was evaluated for five metrics to assess MLC performance. These tests were not performed on the Varian middle strip that was defined with the jaws. Tolerances for each metric evaluated were established based on the results from the multicentre pilot study described in Section 4.9.3 below.

(a) The difference between the measured strip position and the intended strip position. This is defined mathematically as follows: the mean deviation of strip i position c_{ij} from the nominal intended value $c_{nom,i}$ calculated from the average value for each leaf pair j visible on the film (1,…,n) along the same strip i (1,…,5) as

$$\frac{1}{n}\sum_{j=1}^{n}\left(c_{ij}-c_{nom,i}\right) \tag{1}$$

A tolerance of 0.5 mm was established for deviation of strip position from intended.

(b) The deviation between the position of individual leaf pairs and the strip average. This was defined as the positioning bias, and the maximum and minimum values were determined for all leaves visible on each film. This was calculated as the difference between each leaf pair central position and the average of leaf pair central positions for the same strip as

$$\max_{i,j}\left\{c_{ij}+\frac{1}{n}\sum_{j=1}^{n}(c_{ij})\right\} \text{ and } \min_{i,j}\left\{c_{ij}-\frac{1}{n}\sum_{j=1}^{n}(c_{ij})\right\} \tag{2}$$

The tolerance was 1.0 mm for maximum or minimum positioning bias from average. The tolerance was exceeded if either the maximum or minimum was outside of this range.

(c) The SD across all strips for the positioning bias of each MLC leaf pair. The tolerance was 0.25 mm for the SD of the positioning bias for any leaf pair.

(d) The maximum and minimum opening width deviations of leaf pairs. This was calculated as the opening width width of $FWHM_{ij}$ of each leaf pair *j* difference from the mean value $\langle FWHM \rangle_i$ for the same strip *i*

$$\max_{i,j}\left\{FWHM_{ij}-\langle FWHM\rangle_i\right\} \text{ and } \min_{i,j}\left\{FWHM_{ij}-\langle FWHM\rangle_i\right\} \tag{3}$$

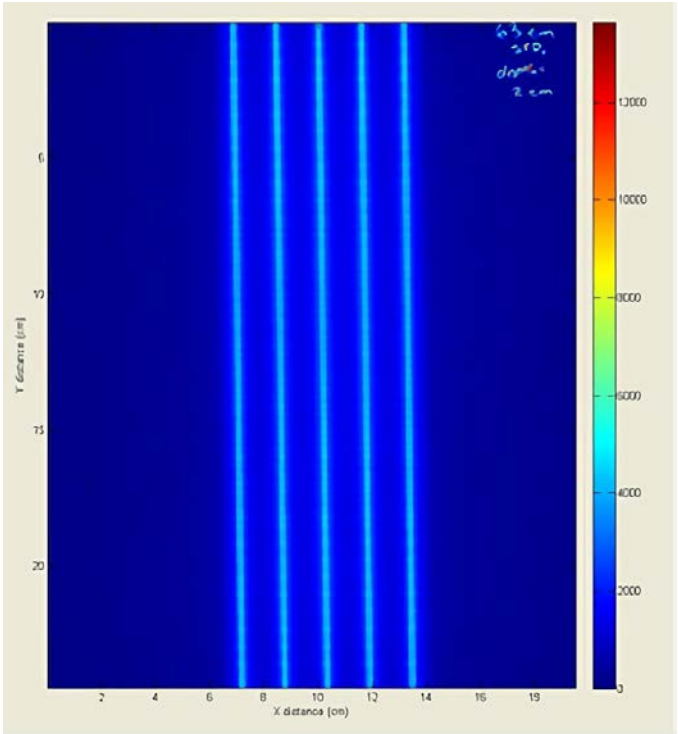


FIG. 48. An example of analysis of a scanned piece of radiochromic film irradiated with a picket fence pattern.

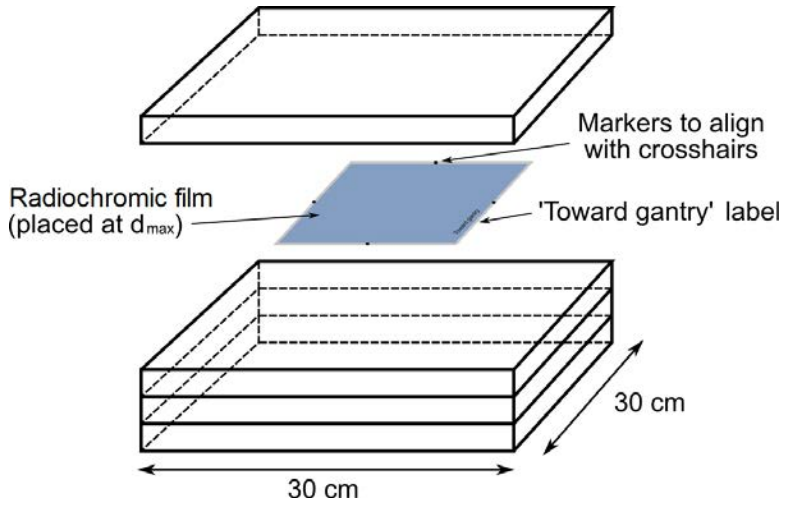


FIG. 49. Placement of the radiochromic film within the slab phantom.

The tolerance was 1.0 mm for the maximum and minimum leaf opening width deviations from the average. The tolerance was exceeded if either the maximum or minimum was outside of tolerance.

(e) The SD of the opening width, FWHM, for each MLC leaf pair. The tolerance was 0.5 mm for the SD of the opening width for all leaf pairs.

4.9.3. Testing of the step 7b audit methodology

Fifteen hospitals from Algeria, Austria, Belgium, Brazil, China, the Czech Republic, Finland, India, Poland, Sweden, Thailand, the UK and the USA took part in the multicentre pilot study, producing 16 sets of results. Twelve of the 15 hospitals used a Varian accelerator; ten had Millennium 120-leaf MLCs, one had an HD-120 MLC and one had a Millennium 80-leaf MLC. The other three institutions used an Elekta accelerator, all of which were equipped with an MLCi 80-leaf MLC. Films were distributed to the participants in the multicentre pilot study by the IAEA Dosimetry Laboratory, and after irradiation they were returned to the IAEA laboratory, which digitized the irradiated films with a flatbed scanner and analysed them with the appropriate software.

The results of the five MLC metrics calculated from the films irradiated in the multicentre study are shown in Figs 50–54.

As can be seen from Figs 50−54, the results of the multicentre pilot study were well within tolerance for four out of five metrics (i.e. for the deviation of the strip position from nominal (Fig. 50), for the leaf positioning bias (Fig. 51), for the positioning bias SD (Fig. 52) and for the SD of the MLC opening width (Fig. 54)).

Two participants (numbers 4 and 14) had one MLC metric outside of tolerance (Fig. 53). The 1 mm limit for the opening width was exceeded. Participant 4 had two leaf pairs out of 60, which were analysed for two strips outside tolerance, whereas participant 14 had three leaf pairs out of 52, which were analysed outside of tolerance. At the same time, participant 14 had the highest SD of the opening width (Fig. 54) among all participants, indicating that the MLC used in the exercise had greater positioning uncertainties compared to others.

4.9.4. Results of the national runs for the step 7b audit

The national audit study included a total of 89 films from four countries (Brazil, China, India and Poland). The films were distributed to local hospitals and, after irradiation, analysed by national DANs. Unfortunately, one of the DANs did not follow the recommended methodology for data analysis and its

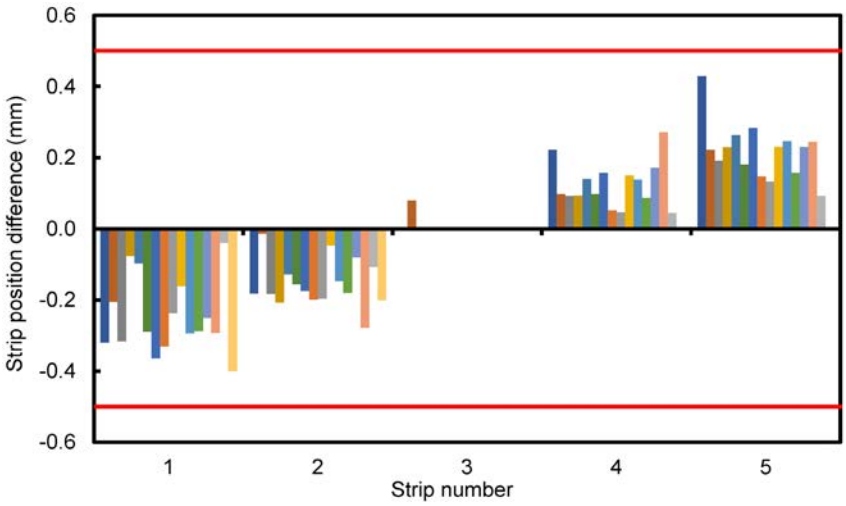


FIG. 50. Deviation of strip position from nominal obtained in the multicentre study. Each bar in each strip represents one participant. The red lines represent the ±0.5 mm tolerance.

11 results could not be compared with others, thus they were excluded from the summary below. The details of the machines used in the national audit runs are shown in Table 18. The results from the national audit runs for the five MLC metrics are summarized in Figs 55–59.

In contrast to the multicentre study, there was a large number of results outside of tolerance for the national audit runs. One country's DAN did not provide all of the correct data, and so that country's results have been excluded from the analysis. There were 24 participants out of 78 (30.8%), which exceeded the tolerance for deviation of strip position from nominal (metric 1). Eleven participants (14%) failed only one strip, seven (9%) failed two, one (1.3%) failed three and five (6.4%) failed four. Four out of 78 (5.1%) exceeded the tolerance for maximum and minimum positioning biases (metric 2). Seven out of 78 (9%) exceeded the tolerance for the SD of positioning bias (metric 3). Nine out of 78 (12%) exceeded the tolerance for maximum and minimum deviations for normalized opening width (metric 4). Five out of 78 results exceeded the tolerance for the opening width SD (metric 5).

As several parameters were used as a measure of MLC mechanical performance, the distribution of the failed metrics per hospital was evaluated (Table 19). There was no consistent pattern of issues noted

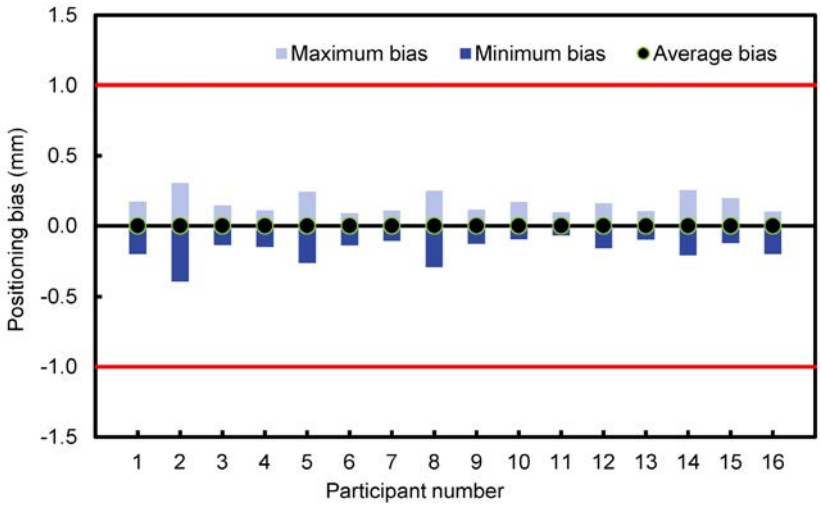


FIG. 51. Maximum and minimum MLC leaf positioning bias for all leaf pair positions visible on films obtained in the multicentre study. The red lines represent the ±1.0 mm tolerance limits.

in different countries. Some countries showed high rates of failure on some metrics, while other countries showed high rates of failure for other metrics.

Finally, the number of metrics failed for each participant's film was determined. The results, broken down by country, are shown in Table 20. There was some overlap in failing metrics, but most often just one metric failed and there were no cases where all five metrics failed. This indicates that the different metrics assessed in this audit are effectively independent and provide complementary information on the geometric accuracy of an MLC performance. Failure in one metric does not mean that that there will be a failure in any other metrics used. This reflects the overall complexity of checking the performance of an MLC, with its various mechanical degrees of freedom depending on MLC design and/or linac model.

4.9.5. Summary and conclusions for the step 7b audit

The results from the national audit runs include many MLCs with poorer performance than those evaluated in the multicentre pilot study. This was seen across all five MLC metrics. Overall, more than 25% of the metrics concerning MLC performance in the national audit runs had at least one result out of tolerance. The good results from the multicentre pilot indicate that MLC performance can readily meet the criteria established in this audit step. That is, these results are very reasonable objectives for national audit study participants to aim for. This may include adjustment or further maintenance of MLCs to achieve optimal performance, which is a prerequisite for highest dosimetric delivery accuracy for IMRT/VMAT. For example, one participant from country 1 who had poor results made a full evaluation, adjustment and maintenance of the MLCs that resulted in improved results upon repetition of this test.

It is obvious that the failure rate is directly dependent on selected tolerance limits. In the AAPM TG 142 report [28], there is only one quantitative tolerance presented: the leaf positioning accuracy of 1 mm for IMRT field delivery. This single leaf positional accuracy was not directly applied as a tolerance limit in the step 7b audit. Instead, a set of three metrics was used to provide an assessment and tolerance similar to this 1 mm value. These three were the average leaf bank position (metric 1), leaf position relative to the average leaf bank (metric 2) and uniformity of leaf opening (metric 4), which were easily analysed from the scanned film.

Execution of the picket fence test revealed challenges during the national audit runs, particularly regarding compliance with the audit step instructions and analysis by different DANs. For example, there were some discrepancies in how the SD was calculated by some DANs; the DAN in country 4 calculated the

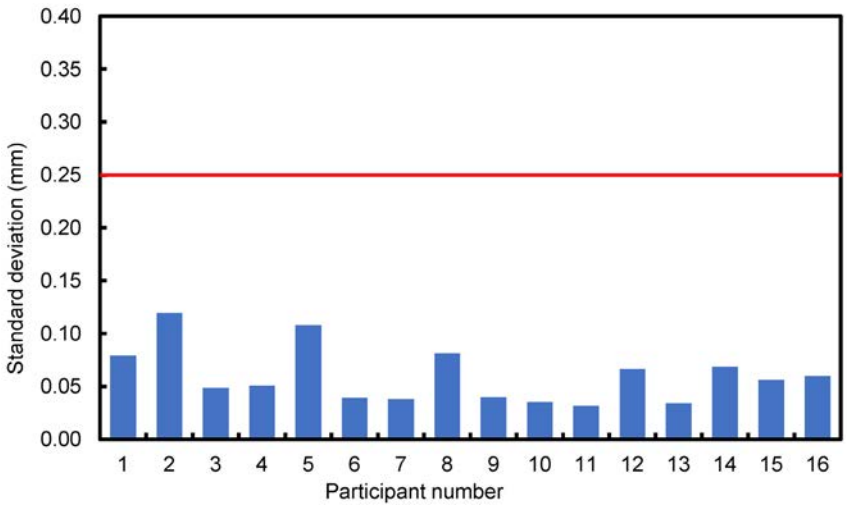


FIG. 52. SD of MLC leaf positioning bias obtained in the multicentre study. The red line represents the ±0.25 mm tolerance limits.

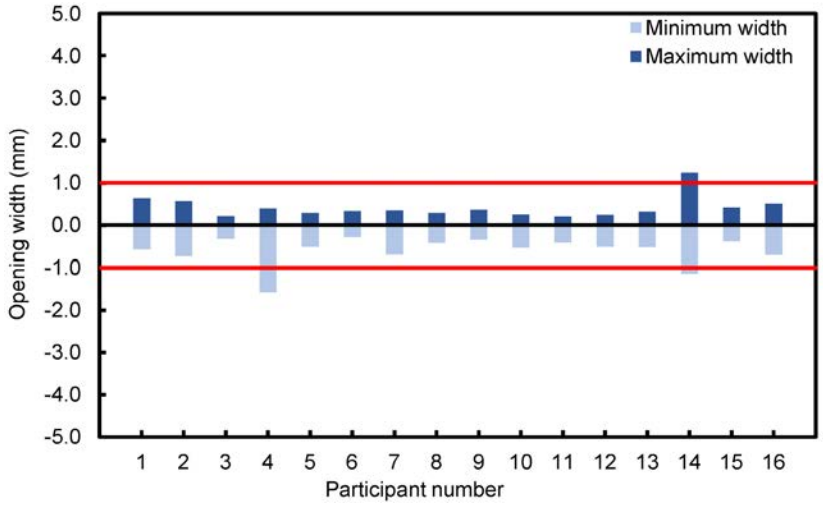


FIG. 53. MLC opening width maximum and minimum deviations from average obtained in the multicentre study. The red lines indicate the ±1.0 mm tolerance limits.

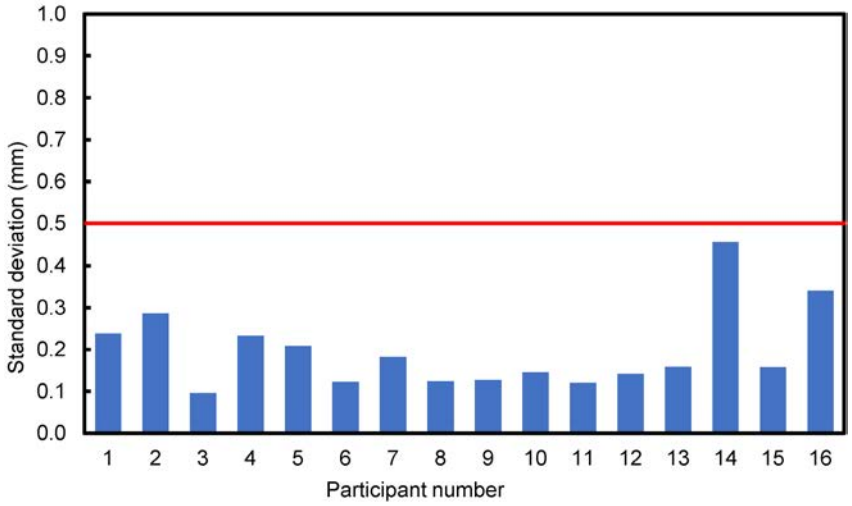


FIG. 54. SD of the MLC opening width. The red line indicates the 0.5 mm tolerance limit.

TABLE 18. DEMOGRAPHICS OF NATIONAL AUDIT STUDY FOR STEP 7B

Country	Number of participants	Varian MLC	Elekta MLC	Siemens MLC
Country 1	15	12	3	0
Country 2	30	16	9	5
Country 3	33	14	12	7
Total	78	42	24	12

SDs from the mean values of the strip, not from individual leaf positions as per instructions. This prevented the data from country 4 from being included in this analysis. For another country (country 3) a picket fence test pattern was provided in digital format to be loaded into each hospital's linac, instead of having the

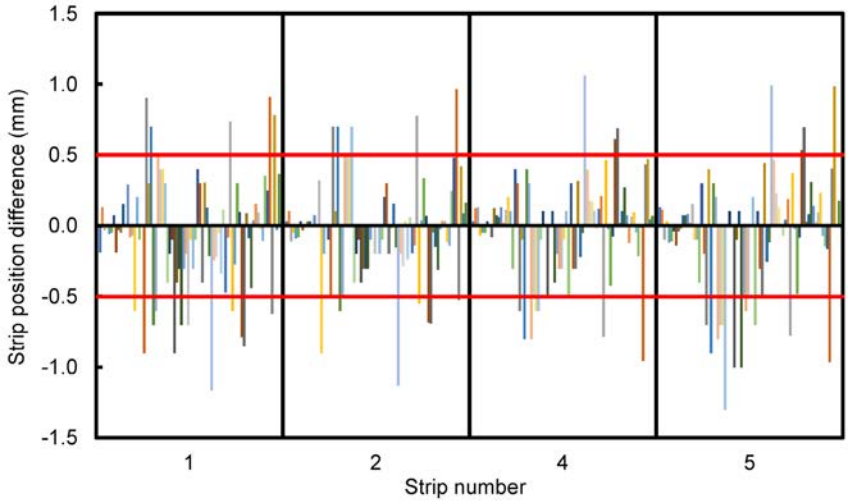


FIG. 55. Deviation of strip position from nominal for national audit study. Results for strips 1, 2, 4 and 5 are normalized to the strip 3 position. A positive shift indicates that the strip position is further away from the centre of strip 3 than intended. The tolerance level of ±0.5 mm is shown.

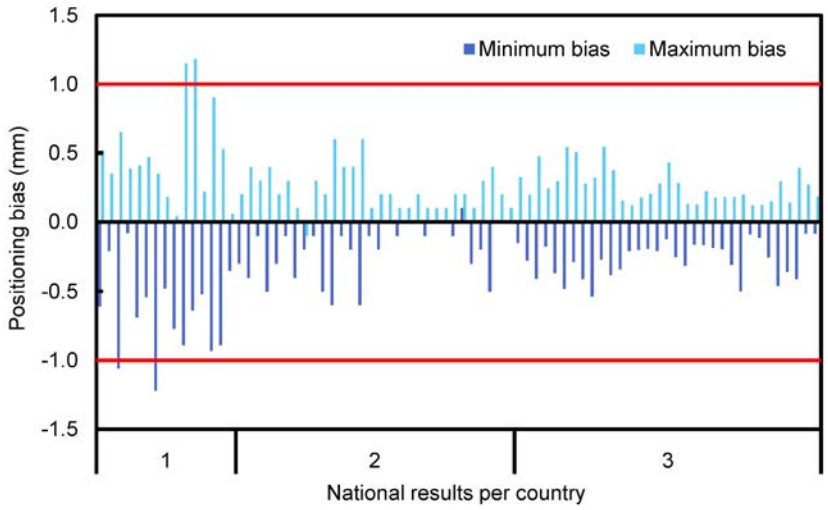


FIG. 56. Maximum and minimum positioning bias for leaf pairs visible on films for national audit study. The red lines represent the ±1 mm tolerance limits.

institution prepare a picket fence pattern. Unfortunately, some of the older linacs in that country could not achieve the narrow leaf opening (5 mm). It is important that the DANs follow the audit methodology and work closely with the institutions to ensure they understand and follow the audit instructions.

Some of the discrepancies between the results in the national audit runs may be explained by the use of different software tools for film evaluation. However, it is expected that the variation in scanner performance and film calibration is of less importance in this step 7b audit than in later steps (8 and 9), since in step 7b the scanned film image is used to detect the strip edge positions, not dose levels.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for the step 7b audit to specify the irradiation conditions and collect the necessary irradiation information (Package 10) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

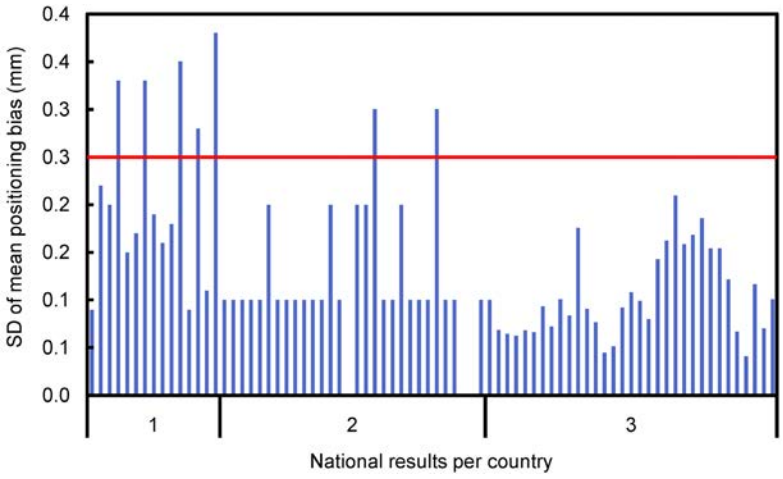


FIG. 57. SD of positioning bias for national audit study. The red line indicates the 0.25 mm tolerance limit.

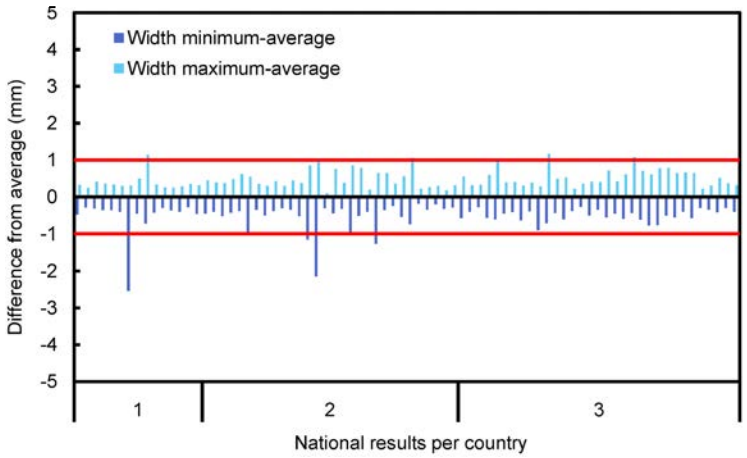


FIG. 58. Opening width maximum and minimum deviations from average for national audit study. The red lines indicate the ±1 mm tolerance limits.

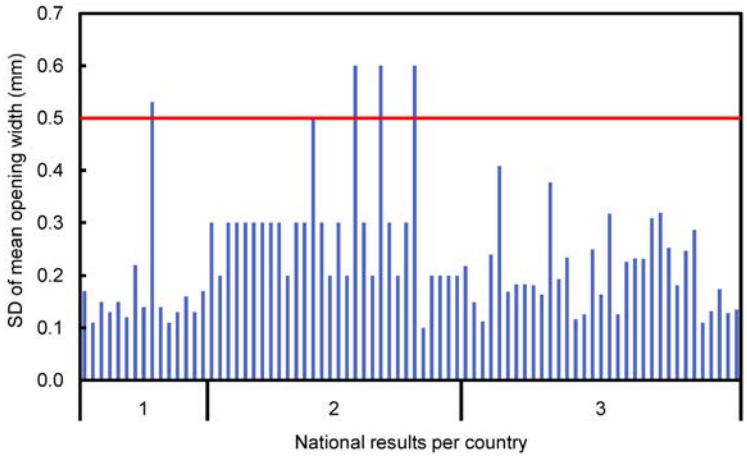


FIG. 59. SD of opening width. The red line indicates the 0.5 mm tolerance.

TABLE 19. DISTRIBUTION OF MULTIPLE FAILURES IN 78 HOSPITALS

Country	*N* hospitals	Category	Mean deviation of strip position (metric 1)	Positioning bias (metric 2)	SD positioning bias (metric 3)	Opening width (metric 4)	SD opening width (metric 5)
Country 1	15	Failure (No.)	0	4	5	2	1
		Ratio	0%	27%	33%	13%	7%
Country 2	30	Failure (No.)	16	0	2	5	4
		Ratio	53%	0%	7%	17%	13%
Country 3	33	Failure (No.)	8	0	0	2	0
		Ratio	24%	0%	0%	6%	0%
Total	78	Failure (No.)	24	4	7	9	5
		Ratio	31%	5%	9%	12%	6%

TABLE 20. FAILURE RATES OF NATIONAL AUDITS (AS % OF TOTAL NUMBER OF PARTICIPATING HOSPITALS IN THE AUDIT RUN) IN DIFFERENT COUNTRIES

Country	*N* hospitals	Category	Failed four metrics	Failed three metrics	Failed two metrics	Failed one metric	Failed at least one metric
Country 1	15	Failure (No.)	0	1	3	3	7
		Ratio	0%	7%	20%	20%	47%
Country 2	30	Failure (No.)	1	1	2	1	5
		Ratio	3%	3%	7%	3%	17%
Country 3	33	Failure (No.)	0	0	0	8	8
		Ratio	0%	0%	0%	24%	24%
Total	78	Failure (No.)	1	2	5	12	20
		Ratio	1%	3%	6%	15%	26%

4.10. STEP 8: FILM QUALITY AUDIT FOR RELATIVE DOSIMETRY OF A PHOTON BEAM SINGLE IMRT FIELD

4.10.1. Introduction to the step 8 audit

The methodology for the step 8 audit for relative dosimetry of a photon beam single IMRT field was developed within CRP E2.40.18, Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery. The national DANs involved as participants in this CRP step were those of Brazil, China, the Czech Republic, India, Poland and Thailand. Other participants from Austria, Belgium, Finland, Sweden, the UK and the USA contributed to the initial development and testing of the methodology.

The purpose of this step was to verify transfer of an IMRT treatment field to the treatment unit, delivery of the treatment field, and agreement between the relative dose distribution delivered and that calculated by the TPS. The evaluation of the relative dose delivery provides an intermediate step between the step 7 audit and a complete 'end-to-end' verification of an IMRT treatment delivery in the step 9 audit. This audit was designed only for fixed angle IMRT dose delivery, not VMAT delivery, and it uses gafchromic film for the relative dose distribution measurements.

4.10.2. Methodology of the step 8 audit

First, a treatment field was selected to be tested. A suitable field was to be chosen by the participating centre and was defined as a highly modulated single treatment field from a recent typical inverse planned IMRT head and neck cancer treatment (e.g. Fig. 60). If IMRT for head and neck treatments was not routinely performed, a highly modulated IMRT field from a different anatomical site could be used. This IMRT treatment field was recalculated to be delivered to a large, solid slab, homogeneous phantom. The treatment field was modified, if needed, to have orthogonal incidence to the top of the phantom. The phantom on which the treatment plan was recalculated could be physically constructed from solid slabs (≥30 cm × 30 cm in width, ≥20 cm thick) of water-substitute plastic and imported into the TPS via a CT scan. Alternatively, a phantom of similar dimension could be virtually created directly in the TPS. The treatment field was positioned on the slab phantom so that the dose distribution was approximately centred on the film. The dose from the treatment field was calculated in the coronal plane at 5 cm depth in the phantom, with the phantom positioned at 100 cm SAD. The maximum dose in this plane was determined to check how many times the field needed to be delivered (the field was used for irradiation repeatedly until a maximum dose of approximately 6 Gy was delivered to this plane).

This film was marked by the auditing body prior to shipping with a label saying 'towards gantry' in the top right-hand corner, to indicate the orientation of the film in the phantom (Fig. 60). As per the calculated treatment plan, the film was placed at a depth of 5 cm in the slab phantom and the phantom was positioned at 100 cm SAD. The film was handled by all persons with appropriate care to ensure no fingerprints or other smudges were made on the film.

The treatment field had to be delivered the appropriate number of times to achieve the desired, approximately 6 Gy, maximum dose to the irradiated area. After irradiation, the film and corresponding TPS dose plan had to be sent to the auditing body for processing and analysis.

In addition to marking, shipping and receiving the film, the auditing body was also responsible for calibrating the film. The calibration curve had to be generated according to the film analysis software manufacturer's instructions over a dose range of 0–10 Gy, for the specific batch of film used for irradiation and using a beam energy appropriate to this audit (typically 6 MV).

Analysis of the institution's film was conducted by loading the film and corresponding TPS dose distribution into the gamma analysis software. Dosimetrically, the measured film distribution had to be normalized to the calculated dose distribution at a point in a high dose, low gradient region. Spatially, the measured and calculated dose distributions had to be aligned to provide optimal agreement in gamma analysis. A relative dose evaluation approach was deemed acceptable for this audit step because the

evaluation was intended to be dosimetric and not focused on set-up. Evaluation of such geometric aspects was included in the step 9 audit (i.e. the complete 'end-to-end' test audit process).

Gamma analysis had to be performed on the dose distributions using a 3%/3 mm criterion over all pixels above 20% of the maximum dose. The acceptability criterion for this exercise was that 90% of pixels needed to pass the gamma criterion. The measured versus calculated dose profiles along the two major orthogonal axes passing through the isocentre were also to be compared (e.g. Fig. 61). Originally, the profile comparison was intended to be quantitative, but this proved to be problematic, which led to this comparison being qualitative.

4.10.3. Development and testing of the step 8 audit methodology

As preparation for the multicentre pilot study, a feasibility study involving the comparison of scanners and film analysis software was first conducted among a core group of consultants and the IAEA Dosimetry Laboratory to assess the variability on the final gamma evaluation, select a suitable set of parameters for the study and help to interpret the results from different DANs. Participants used the following types of film analysis software: Film QA Pro, Mobius Doselab, RIT113, OmniPro IMRT and an in-house developed software, combined with flatbed scanners recommended for EBT film evaluation. For this purpose, one film pre-irradiated with an IMRT field by the IAEA, plus associated calibration films, were circulated among the five centres participating in the study. Each centre generated a calibration curve based on the calibration films and applied this to the IMRT film. Gamma analysis was performed for the following gamma parameter settings: 3%/3 mm, 2%/2 mm using both local and global dose differences, two different regions of interest (full image of Fig. 60 and a smaller 12 × 12 cm^2 region of interest focused on the highest doses), normalization methods (isocentre, arbitrary point, optimal point), thresholds (all isodoses and low dose thresholds of 10%, 20%, 30% and 50%), colour channel(s) used and resolution (72 dpi, 150 dpi). However, not all analysis software could implement all of these combinations. The initial evaluations of gamma pass rates between the feasibility study participants (based on a single film circulated to the different groups)

FIG. 60. Sample highly modulated head and neck IMRT field used for this audit step.

were evaluated for the different criteria, utilizing the five different commercial and in-house software tools mentioned above. There was a marked lack of consistency in the gamma pass rates depending on gamma evaluation criteria, software or dose threshold applied, with up to 30% differences observed between the systems and evaluation methods. In general, smaller deviations (up to 15%) were observed when the analysis was limited to a smaller region of interest (12 × 12 cm^2) centred around the high dose region.

Due to the substantial variability seen in the results between the five centres participating in this exercise, a follow-up study was designed. The purpose of this study was to remove the influence of different individual approaches involved in the gamma analysis process. This was done by irradiating three films at a single location (Medical University of Vienna/AKH Vienna) and scanning and analysing them in one centre (IAEA Dosimetry Laboratory). Three different scanners (11000XL, 750Pro, 4990) and three different software packages (Film QA Pro, Verisoft, RIT113) were used, as were a variety of gamma criteria (dose difference, distance to agreement, low dose threshold, global versus local dose difference) and numbers of calibration steps in the film calibration curve.

Across the different software packages but using a single scanner, differences of up to 6% in the number of pixels passing were seen (depending on the gamma criteria). Across the different scanners but using a single software package, differences of up to 3% in the number of pixels passing were seen (again, depending on the gamma criteria). Based on these results, it was concluded that different scanner and software conditions could, in total, be expected to introduce at least 7% variability into the calculation of the percentage of pixels passing gamma.

Based on the results of the two preliminary studies above, detailed instructions were prepared for the DANs, and the importance of a consistent film evaluation procedure, with proper calibration and scanner corrections, was emphasized. These instructions were based on global gamma criteria 3%/3 mm, 20% threshold with respect to maximum dose on film, film normalization in the high dose region and a gamma passing rate of 90%. Even with these controls applied to minimize variations, it was recognized that differences of approximately 7% could still be expected between software programmes and scanners.

The multicentre study was then conducted, involving both the CRP consultants and DANs, with the purpose of testing the methodology in a broader group. Sixteen institutions were given a sheet of radiochromic film for irradiation with a single highly modulated IMRT field. TPS calculations and film irradiations were performed using eight different accelerator models, six MLC models, four TPS models and five dose calculation algorithms. An overview of the equipment used in the multicentre pilot study is given in Table 21. Irradiated films were returned to the IAEA Dosimetry Laboratory, where they

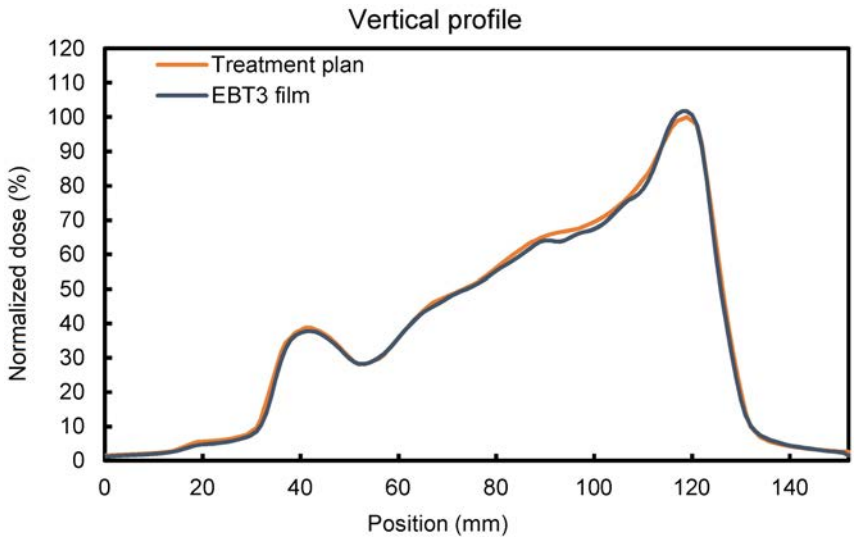


FIG. 61. Example of profile comparison, including TPS-calculated dose distribution and measured dose distribution for an IMRT head and neck field.

were scanned (using an Epson 11000XL scanner) and analysed (using Ashland FilmQA Pro). Gamma analysis was performed, as decided from the initial feasibility study, using 3%/3 mm dose difference and distance-to-agreement criteria and an isodose threshold of 20% with measured and calculated dose distributions matched to give the best visual fit of isodose lines.

Following these preliminary studies and based on the gamma analysis criteria established for the methodology of this audit step, the full multicentre study was completed. The gamma passing rate for all centres ranged between 95.4% and 100%, exceeding the acceptance limit of >90% of pixels passing gamma. Orthogonal profiles through the isocentre were also examined, some of which revealed dose differences between the TPS-calculated and measured doses, whereas gamma results remained above 95%. A representative example of horizontal profiles (in the L–R direction across the film) for a head and neck IMRT plan, with considerable discrepancies (close to 10%) between the calculated and measured relative dose values, is shown in Fig. 62.

TABLE 21. EQUIPMENT OVERVIEW FOR MULTICENTRE STUDY OF STEP 8

Linac manufacturer	Number	MLC model	Number	TPS	Number	TPS algorithm*	Number
Varian	12	Millennium 120	10	Eclipse	11	AAA	9
Elekta	4	HD 120	1	XiO	2	S/C	3
		Millennium 80	1	Monaco	2	Monte Carlo	2
		MLCi	2	Pinnacle	1	GBBS	1
		MLCi2	1			Pencil Beam	1
		Agility	1				

* AAA — analytical anisotropic algorithm, S/C — superposition/convolution, GBBS — grid-based Boltzmann solver.

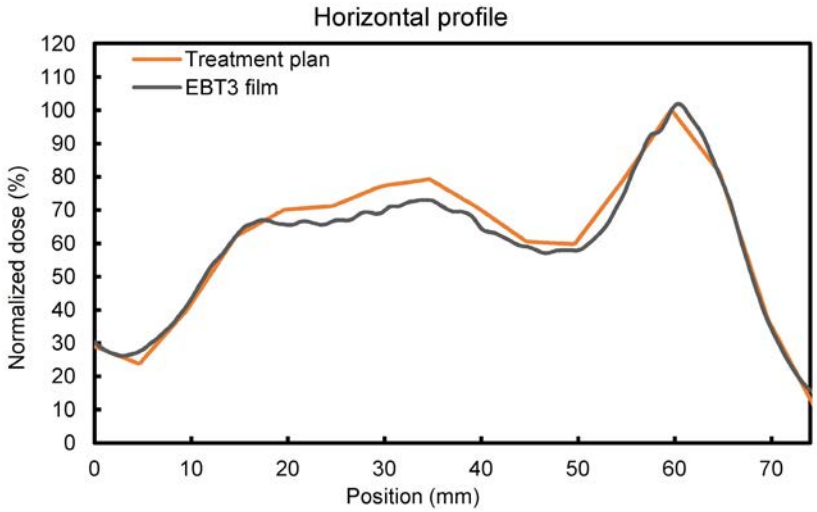


FIG. 62. Example profile showing discrepancy between TPS-calculated film profile and that measured with film.

TABLE 22. EQUIPMENT OVERVIEW FOR THE NATIONAL AUDIT RUNS OF THE STEP 8 AUDIT

Country	Number of institutions	Data sets	Number of TPSs	Accelerator manufacturers			Energies (MV)
				Varian	Siemens	Elekta	
Country 1	13	15	2	13	0	2	6, 10
Country 2	30	30	6	15	5	10	6
Country 3	2	2	1	2	0	0	6
Country 4	11	11	3	6	2	3	6, 15
Total	56	58	6	36	7	15	

4.10.4. Results of the national runs for the step 8 audit

After the completion of the multicentre pilot study, the national audit runs were implemented in four countries: Brazil, China, the Czech Republic and Poland). A total of 56 centres from four countries irradiated 58 IMRT films. The information on the linacs and TPSs used in the national audits are shown in Table 22.

The DAN in country 1 scanned films with a V750Pro flatbed scanner and performed all film analysis with its in-house developed software. Details on the software functionality, the underlying algorithms and its features can be found in Ref. [159]. The DAN in country 2 performed film analysis using Film QA Pro and an Epson 11000XL scanner. The DAN in country 3 used OmniPro software and an Epson 11000XL scanner. However, it did not follow recommended and consistent analysis methods. This DAN used a 4%/3 mm gamma criteria (instead of 3%/3 mm); used a 10% low dose threshold for one film and a 15% low dose threshold for the second film, instead of a 20% low dose threshold for both films; and scanned the calibration films with a Vidar scanner instead of scanning both the calibration and experimental films with the same scanner, as is part of good film practice. The DAN of country 4 used Film QA Pro for gamma analysis and an Epson 11000XL scanner.

As mentioned above, results of the national audit runs were provided for 58 IMRT films evaluated in this audit step. In a total of five of the results, it was found that less than 90% of the pixels passed the established gamma criteria. The passing rates presented by country, corresponding to the equipment and analysis software described previously, are shown in Table 23.

4.10.5. Summary and conclusions for the step 8 audit

This step was designed primarily to prepare the DANs for the step 9 audit as a training exercise on consistent film handling and management.

Initial evaluations showed, rather dramatically, that even if consistent film handling and gamma analysis was implemented, different gamma results were found. More specifically, the percentage of pixels passing gamma was found to substantially depend on how the film was scanned, what gamma analysis software was used and what gamma criteria were used. This variability can be minimized in an audit setting by ensuring that as much consistency and uniformity exists as possible. However, the results of the preliminary studies in this audit step show that comparing results between different audit networks may be challenging because of the differences that are likely to exist.

Given that the primary purpose of this audit was as a training exercise on film handling and management, the audit step was successful in the national audit setting. Most of the DANs were able to implement consistent film readout and gamma analysis processes. However, one DAN in particular was

TABLE 23. DETAILS OF THE GAMMA PASS RATES BY COUNTRY PARTICIPANT

Country	Number of institutions	Data sets	Gamma passing rate		Results outside acceptance criteria	
			Mean	SD	Number	%
Country 1	13	15	95.1	0.080	2	13%
Country 2	30	30	92.5	0.076	3	10%
Country 3	2	2	97.2	0.041	0	0%
Country 4	11	11	99.3	0.004	0	0%
Total	56	58	94.7	0.072	5	9%

not able to demonstrate uniform analysis (or even proper film handling techniques), which are critical in an audit setting.

Although this audit was designed for static gantry IMRT, many participants were able to implement VMAT into the audit by delivering an entire arc collapsed to a single fixed gantry angle. In this manner, this audit could be broadly extended to dynamic treatments.

The tolerance of 90% of pixels passing the 3%/3 mm criteria was found to be adequate throughout this audit step. However, as the percentage of pixels passing gamma will depend strongly on the manner of scanning and the software used, the gamma acceptance criteria may need to be re-evaluated for a given DAN based on its specific tools and methods.

The detailed instruction sheets, data sheets and results reporting forms that were prepared for audit step 8 to specify the irradiation conditions and collect the necessary irradiation information (Package 11) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

4.11. STEP 9: 'END-TO-END' DOSIMETRIC QUALITY AUDIT FOR IMRT, INCLUDING IMAGING, TREATMENT PLANNING AND DELIVERY

4.11.1. Introduction to the step 9 audit

The methodology for the audit step 9 'end-to-end' dosimetric quality audit for IMRT, including imaging, treatment planning and delivery, was developed within CRP E2.40.18, Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery. The national DANs involved in this CRP step were those of Brazil, China, the Czech Republic, India, Poland and Thailand. Other participants from Austria, Belgium, Finland, Sweden, the UK and the USA contributed to initial development and testing of the methodology.

The purpose of this step was to carry out an 'end-to-end' test of IMRT delivery, including VMAT. A custom-built phantom was made that was designed to contain both film and TLD capsules, employing both of the previously established dosimetry verification methods. In this way, both the dosimetric and spatial accuracy of the dose delivery could be tested together, as well as the planning, alignment and delivery processes.

FIG. 63. Phantom containing IMRT QA insert loaded with film and TLDs, and a pillbox with TLDs to be affixed to the outside of the phantom.

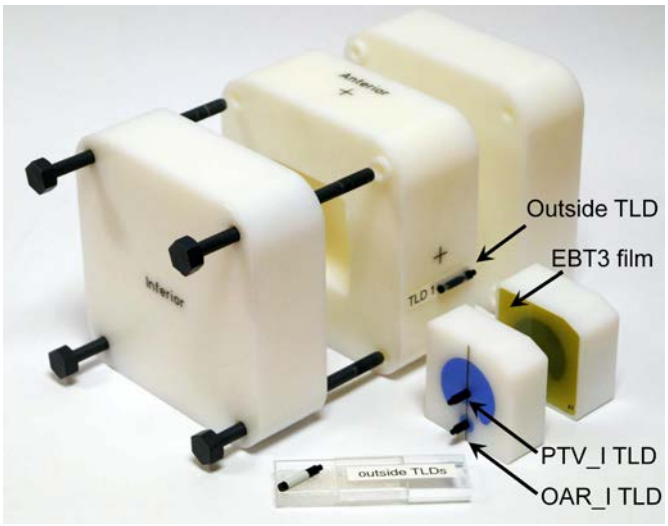


FIG. 64. Phantom disassembled to show insert for the film and TLDs (reproduced from Ref. [105]).

4.11.2. Methodology of the step 9 audit

A solid polystyrene slab phantom, specific for this purpose, was designed and manufactured by the IAEA. The phantom, pictured in Fig. 63, was labelled with anatomical orientations to facilitate positioning during the planning CT scan and irradiation. The phantom contained a structure (see Fig. 64, reproduced from Ref. [105]) intended to mimic a patient planning target volume (PTV) [160] to which a high dose was to be delivered. Close and posterior to the PTV was another structure intended to mimic an organ at risk (OAR) [160], which was to receive a dose that was limited within well-defined dose constraints. The PTV section of the phantom was constructed in such a way that two TLD capsules could be inserted parallel to the axis of the phantom. The OAR also had provision for the insertion of two additional TLD capsules. The central axial slice of the PTV contained a piece of radiochromic film sandwiched between the two halves of the PTV and OAR structure. It was therefore possible to position TLD capsules within each of the two halves of the PTV and OAR, superiorly (PTV_S and OAR_S) and inferiorly (PTV_I and OAR_I) to the film.

Labels were taped to the outside of the phantom to indicate the intended locations of two additional TLD capsules. These outside TLDs were to be fixed to the phantom during the CT planning scan of the phantom and then removed prior to the subsequent IMRT delivery. In this way, the dose to the internal TLDs resulting from the CT scan (which would not be included in the treatment plan) could be estimated and subtracted during the analysis. One TLD with a white label, shown in Fig. 64, was included with the phantom during the mailing process to account for any background radiation during transport.

The IMRT phantom was CT scanned for treatment planning purposes, as though it were a patient who was to undergo IMRT treatment for a head and neck cancer in the clinic (i.e. using the same scan parameters). The CT scan data were exported to the TPS and the internal structures, including the TLD powder in the capsules, were contoured. An IMRT plan was produced using the same planning process and parameters as would be used for a patient. The aim was to deliver 4 Gy in two fractions to the PTV, while limiting the dose to the OAR. The dose constraints for one fraction were:

— PTV: 2.0 Gy prescription dose to at least 95% of the PTV volume, and <1% of the PTV is to receive <93% of the prescription dose;
— OAR: ≤1.4 Gy maximum dose;
— Maximum dose anywhere in the plan: ≤2.2 Gy.

Local pretreatment QA checks were performed as for a patient plan. The phantom was then set up on the treatment couch using the alignment marks and noting the anatomical labels. Two fractions of the planned IMRT treatment were delivered to the phantom.

The phantom and its contents, all of the TLD capsules and the TPS data of the axial and sagittal isocentric plane dose distributions, were then returned to the auditing centre for analysis.

4.11.3. Development and testing of the step 9 audit methodology

As an initial step to assess the step 9 audit methodology, the impact and management of the imaging dose from the simulation CT was evaluated. Estimation and management of the signal to the TLD in the PTV and OAR from the imaging dose was dealt with by placing additional TLD on the outside of the phantom. The signal measured by the external TLD, corrected to the internal TLD position, could then be subtracted from the internal TLD. The importance of this imaging dose became clear during the testing of the methodology, as some centres delivered considerably more imaging dose than was expected (in excess of a factor of ten more than from lower dose scans). Imaging TLD signals were high enough to contribute substantially to overall TLD-measured dose (as much as 20% of the OAR dose). An initial evaluation compared the signal from the external TLD to the internal TLD from various imaging scanners and protocols. This issue is complex because the dose changes throughout the phantom, but so too does the energy spectrum, which also impacts on the signal recorded by the TLD (as it has a higher Z_{eff} than tissue). For a range of clinical CT scan protocols, the ratio of the signal from the internal TLD to the external TLD ranged between 1.07 and 1.21, with an average value of 1.13 across the different scan protocols. Given this variability and the opportunity to avoid reading additional TLD, an evaluation was conducted to examine whether scanner-reported CT dose index (CTDI) values could be used to evaluate the dose of the external TLD. Unfortunately, scanner-reported CTDI values did not correspond to TLD signals particularly clearly. The weak correlation between TLD signals and scanner-reported CTDI values from centres participating in methodology testing is observed in Fig. 65 (reproduced from Ref. [105]). As a result of this imaging study, the imaging dose should be accounted for by using external TLD on the phantom during imaging and subtracting 1.13 times the external TLD signal from the PTV and OAR TLD in the phantom. Of note, this relationship of 1.13 was determined for lithium fluoride (LiF) based TLD (e.g. TLD-100). If a different dosimeter is used (with a substantially different Z_{eff}), the ratio of outside to inside dosimeter signal needs to be evaluated to determine the appropriate correction factor.

The multicentre pilot study included irradiation of the IMRT phantom by 16 institutions from Austria, Belgium, Brazil, China, Cuba, the Czech Republic, Finland, India, Poland, Sweden, Thailand, the UK and the USA.

Some of the multicentre participating institutions carried out an additional series of measurements after the delivery of the IMRT to the phantom. The phantom was dismantled to remove the TLD capsules and radiochromic film. The phantom was then reassembled, with the inferior slab substituted for one that had access holes drilled such that a small IC could be inserted. The chamber could be placed in the same positions as the TLD capsules had been, and direct dose measurements were made during repeated delivery of the IMRT prescription. Equipment information for the multicentre study participants is shown in Table 24.

When the TLD results in the PTV were compared to the IC results in the PTV, very good dose agreement was found. The average difference between these two dosimeters was 0.4%, with a SD in this difference of 1.2%. This further reinforces the robustness of the TLD programme, particularly as applied to this audit step.

An additional study was done by a subset of groups (i.e. those who performed the IC measurements) to assess the sensitivity of the positioning of the phantom on the predicted dose distribution. This was done by calculating the volumetric dose data for the TLD structures with isocentre moves of 1 mm in the anterior, posterior, and right and left lateral directions. The results of these calculations are shown in Fig. 66. These results highlighted that the dose to the PTV was quite insensitive to set-up variations in the phantom, indicating robust results for the PTV. In contrast, higher dose variations in the OAR reaching over 10% were observed. The ratio of measured to calculated OAR dose was therefore highly sensitive to any set-up variations of the phantom. Consequently, no tolerance limit was adopted on the measured to calculated dose for the OAR, and rather a measured dose tolerance of 2.8 Gy was established.

The films were analysed using previously established methods (step 7 and 8 audits). A successful gamma result was >90% pixels passing a 3%/3 mm gamma evaluation using a 20% low dose threshold. For the multicentre study, the film normalization was done to the average TLD dose in the PTV and not as a relative dose comparison. Consequently, TLD dose differences were incorporated into the gamma analysis.

The gamma analysis results were re-evaluated for nine phantom plans (nine of the participants) using various dose differences, distances to agreement and low dose threshold criteria. In particular, permutations of 2% and 3% dose difference, 2 mm and 3 mm distance to agreement and 20% and no low dose thresholds were investigated. The results of these different combinations are shown in Fig. 67. As expected, tighter gamma criteria resulted in fewer pixels passing gamma. In general, all the results

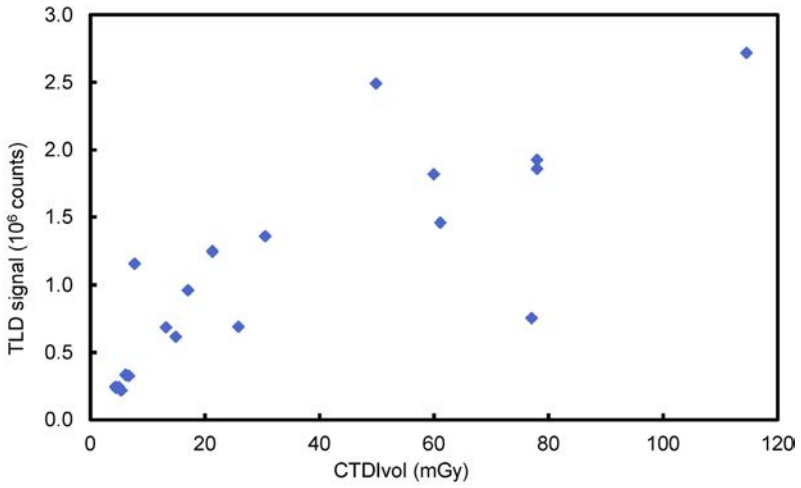


FIG. 65. The relationship between $CTDI_{vol}$ and TLD signal from a series of different scan protocols (reproduced from Ref. [105]).

TABLE 24. MULTICENTRE STUDY PARTICIPANTS' EQUIPMENT

Centre	Linac	MLC	IMRT technique	Energy (MV)	TPS	Algorithm	IC
1	Elekta Versa HD	Agility	VMAT	10	Monaco	XVMC 1.6	IC Semiflex
2	Varian Truebeam STx	HD 120	VMAT	6	Eclipse	Acuros XB 10.0.28	
3	Varian Clinac iX	Millennium 120	dMLC	6	Eclipse	AAA	IC PinPoint 31006
4	Varian Truebeam	Millennium 120	VMAT	6	Eclipse	AAA	
5	Varian iX	Millennium 120	VMAT	6	Eclipse	AAA	
6	Elekta Agility	Agility	VMAT	6 FFF	Monaco	Monte Carlo	IC Semiflex
7	Varian 21EX	Millennium 120	S&S	6	Pinnacle	CC convolution	IC A1SL
8	Varian Truebeam	Millennium 120	VMAT	6	Eclipse	AAA	
9	not reported	Millennium 120	VMAT	6	Eclipse	not reported	
10	Elekta Synergy	160 leaves	S&S	6	XiO	Superposition	
11	Varian Clinac DHX	Millennium 80	dMLC	6	Eclipse	PBC 8.6.15	
12	Varian Novalis TX	HD MLC	dMLC	6	Eclipse	AAA	
13	Varian iX	Millennium 120	VMAT	6	Eclipse	AAA	
14	Varian Truebeam	Millennium 120	dMLC	6	Eclipse	AAA	
15	Varian Clinac iX	Millennium 120	dMLC	6	Eclipse	AAA	
16	Varian Clinac 2300 C/D	Millennium 120	dMLC	6	Eclipse	AAA 10.0.28	

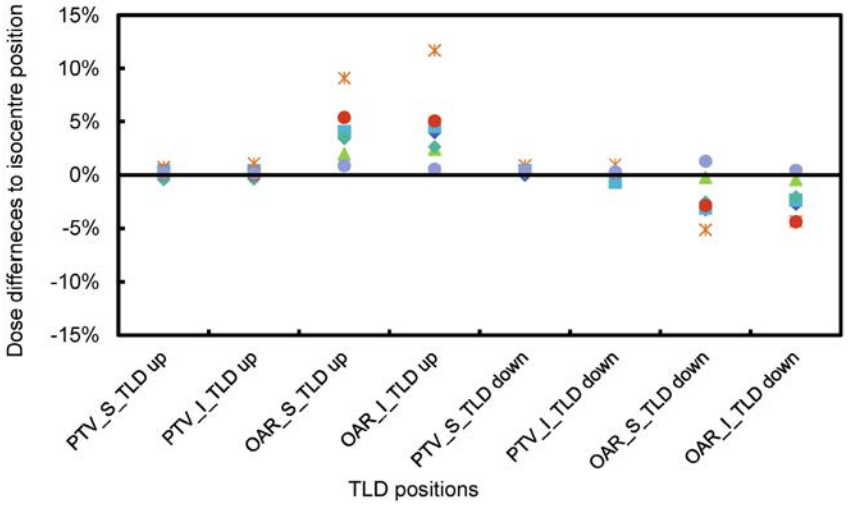


FIG. 66. Impact on the calculated dose at the locations of the TLD associated with a shift in the phantom of 1 mm anterior (up) and 1 mm posterior (down). Symbols in the graph correspond to seven different phantom plans.

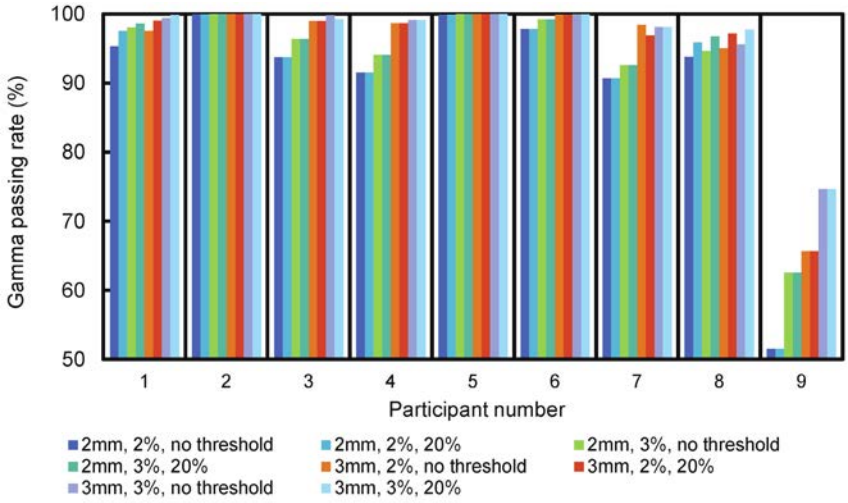


FIG. 67. Percentage of pixels passing various gamma criteria for a selected group of participants.

were consistent, and a result of a relative comparison of institutions did not depend on evaluation criteria. There was no observed reason to alter the initially proposed gamma criteria of ≥90% of pixels passing 3%/3 mm with a 20% low dose threshold.

Dose profiles were read from the films and compared to the TPS-generated profiles. For the multicentre study, these were displayed as the dose normalized to the average TLD result in the PTV, but for the national audit study it was changed to normalize both sets of data at the maximum plan dose.

TLD processing was carried out using the methods developed in previous steps. The pass criterion was a result within 5% of the volumetric dose reported by the TPS for each TLD in the PTV. The TLD results for the multicentre study (including three repeated irradiations) are shown in Fig. 68 (reproduced from Ref. [105]). The ratios of measured to calculated doses (and SD) for each TLD location are given in Table 25. All TLD results in the PTV were within the previously established ±5% criterion, except for one institution (one TLD was 7.8% higher than calculated, the other TLD was 6.3% higher than calculated). While more variability was seen in the agreement between the measured and calculated dose to the OAR, all of these results were still below the 2.8 Gy threshold criterion. The maximum dose measured in the OAR from any of the multicentre irradiations was 2.15 Gy (23% lower than the threshold criterion).

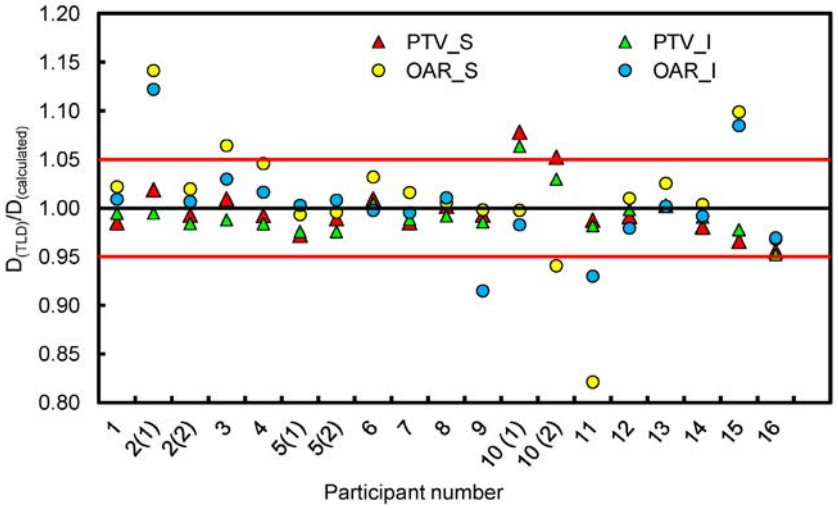


FIG. 68. TLD results (ratio of measured to calculated doses). Results for each institution include four TLD locations, two in PTV (PTV_S, PTV_I) and two in OAR (OAR_S, OAR_I). The ±5% tolerance level is shown in red. Institutions 2, 5 and 10 include initial (1) and repeated (2) irradiation results (reproduced from Ref. [105]).

TABLE 25. AVERAGE RESULTS FOR MULTICENTRE IRRADIATIONS, INCLUDING TLDS IN THE PTV AND OAR

Location	Mean	SD
PTV_S	0.998	0.028
PTV_I	0.993	0.023
OAR_S	1.010	0.063
OAR_I	1.003	0.047

Two centres (2 and 10 in Fig. 68) repeated their irradiations, one due to high disagreement between the measured and calculated doses in the OAR TLDs and the other due to high disagreement between the measured and calculated doses in the PTV TLDs, respectively. One centre (5 in Fig. 68) repeated their irradiations and showed consistent results.

Films irradiated by 16 participants in the study were analysed. Two institutions failed the gamma analysis criterion of >90% pixels passing at 3%/3 mm. The vertical (anterior–posterior) profile results derived from the films are shown in Fig. 69 for the two multicentre irradiations that failed gamma analysis. Of note is that for the multicentre study, the film normalization was done to the average PTV TLD dose and not done as a relative dose comparison. Consequently, TLD dose differences were incorporated into the gamma analysis. Institution 10 had an average measured to calculated dose of 1.07 in the PTV (Fig. 68), causing the film profile to be substantially higher than predicted and only 86% of pixels to pass gamma. Institution 16 had an average measured to calculated dose of 0.955 in the PTV, causing the film profile to be substantially lower than predicted and only 75% of pixels to pass gamma. For the national audit runs, it was proposed to specify that the film and TPS calculation be normalized to the maximum planned dose. Using this approach, the profiles will always agree at this point; this decouples the gamma result (relative dose distribution) and the TLD dose (absorbed dose). When this relative normalization approach was used, the gamma results from both institution 10 and institution 16 would have 99% and 100% of pixels passing, respectively. The impact of this relative normalization on the profiles for institutions 10 and 16 is shown in Figs 69(c) and (d).

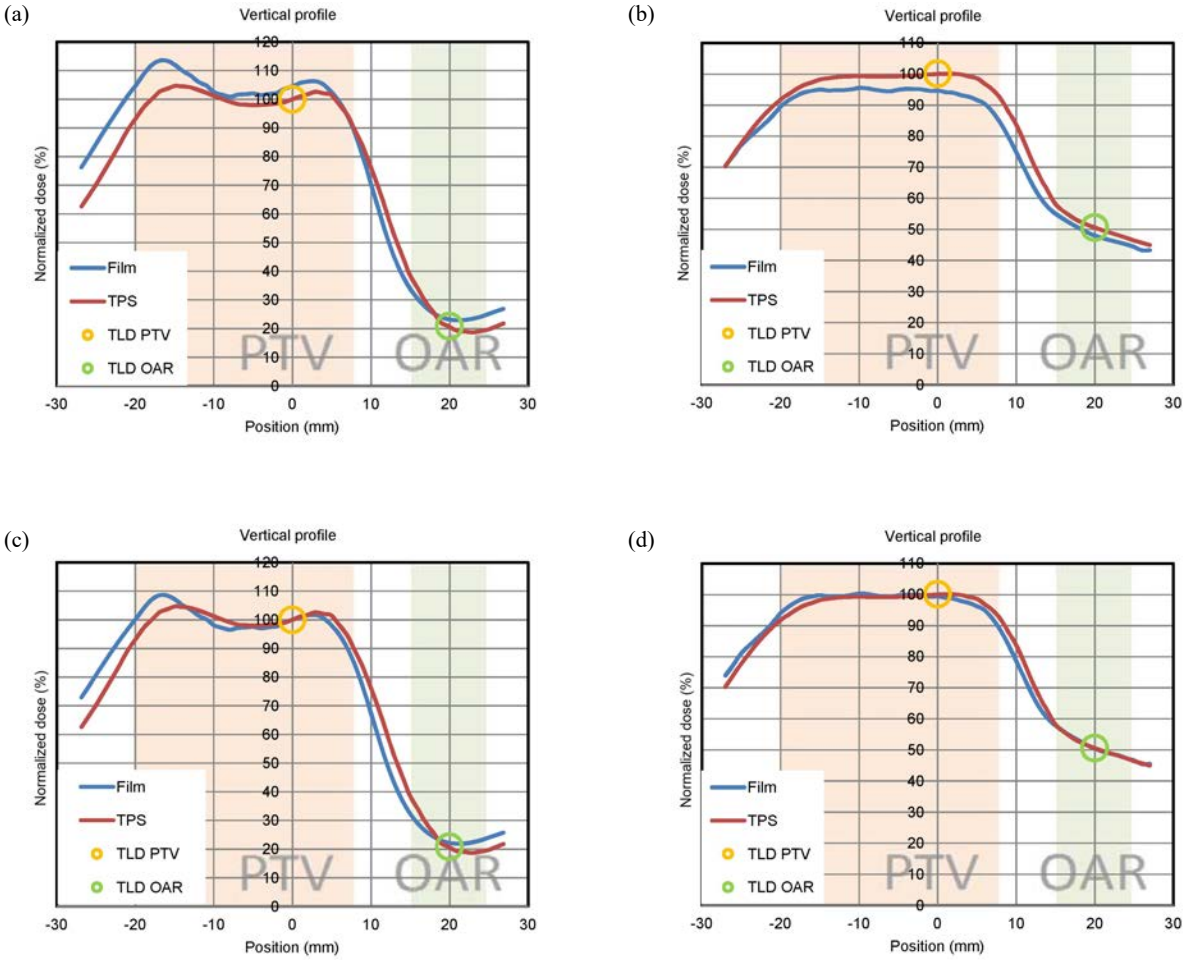


FIG. 69. Measured and calculated dose anterior–posterior profiles for the two multicentre irradiations that failed gamma analysis. (a, b) Film normalized to average PTV TLD dose. (c, d) Film normalized at plan maximum. Results for institution 10 are shown in the left column (a, c) and results for institution 16 are shown in the right column (b, d).

4.11.4. Results of the national runs for the step 9 audit

The national audit runs included irradiation of the phantom by 64 institutions in six countries (Brazil, China, Cuba, the Czech Republic, India and Poland). Each institution received the phantom already containing film and TLDs. Institution staff were required to attach the external TLD capsules for the planning CT scan, then remove them for treatment delivery. No further manipulation of the phantom was necessary, with all of the assembly and disassembly being done by the DANs.

The TLD results for the 64 institutions in six countries are shown in Fig. 70 (reproduced from Ref. [105]). In the majority of cases the PTV TLD results were within the 5% acceptance limit. However, some centres exceeded the 5% limit; the worst case (country 6 in Fig. 70) had both PTV and OAR TLD results outside 5% tolerance, measuring a substantially greater PTV dose than that predicted by the TPS, by as much as 26%. In total, 17 out of the 64 institutions (27%) failed to meet the PTV TLD agreement criteria of 5% to the TPS-calculated dose. None of the OAR TLDs exceeded the OAR dose constraint of 2.8 Gy.

The 64 gamma analysis results from the national runs are shown in Fig. 71. Seven centres failed to achieve the 90% pass rate for 3%/3 mm using a 20% low dose threshold. One institution managed to only achieve 10% of pixels passing this gamma criterion. This was followed up at the national level.

Twenty-two institutions (34%) failed the audit in that they did not meet either the TLD or the gamma criteria. Two institutions failed both the film gamma and TLD criteria. For country 6, three of the

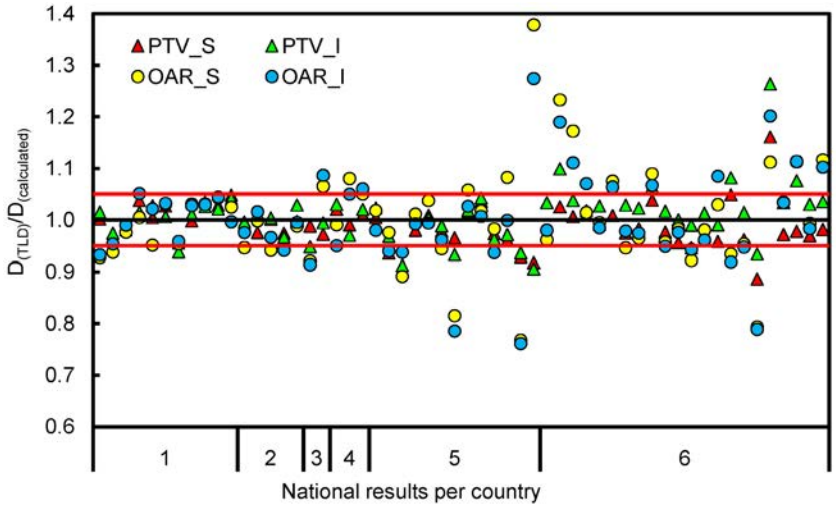


FIG. 70. TLD results (ratio of measured to calculated doses). Results for each institution include four TLD locations, two in PTV (PTV_S, PTV_I) and two in OAR (OAR_S, OAR_I). The ±5% tolerance level is shown in red (reproduced from Ref. [105]).

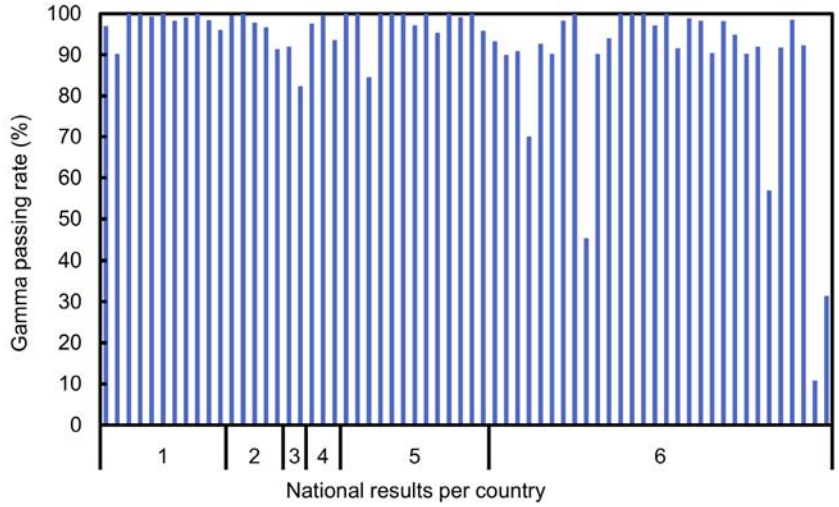


FIG. 71. Gamma results for the national audit runs. Seven of the participating institutions failed to achieve the 90% pass rate for the chosen criteria.

EBT3 film results showed gamma passing rates below 50%, but TLD results were within the 5% limit. This suggests issues with film handling at the national level rather than dosimetric problems.

4.11.5. Summary and conclusions for the step 9 audit

Based on the multicentre pilot study, agreement within ±5% between the measured and calculated doses was broadly achievable for the TLD in the PTV (see results summarized in Table 25), indicating that a ±5% tolerance is appropriate. For the TLD in the OAR, the sensitivity study indicated clearly that an agreement criterion based on the measured to calculated ratio was too demanding based on the uncertainty associated with a 1 mm set-up error. The multicentre study and national audit runs both indicated that a dose below 2.8 Gy was readily achievable (even including the uncertainty associated with set-up) and was therefore an appropriate tolerance.

The profiles are valuable for identifying regions of disagreement and misalignment between the measured and calculated dose distribution. The gamma criteria provided reasonable results and the gamma tolerance limits were adequate.

The agreement achieved in TLD results can be directly compared with IMRT audits conducted by IROC-H using a remote head and neck anthropomorphic phantom. In the current audit, 25% of participants in the national runs had TLD results in the PTV that were outside of the 5% tolerance. Recent IROC-H results, evaluated using a 5% tolerance on the TLD results in the PTV, showed a similar failure rate of 20% [41].

In some facilities it was reported that the irradiation process was conducted entirely by the physics personnel. It should be emphasized during this audit that this phantom test should be conducted in the manner in which patients are treated. Importantly, the various steps of this audit need to be conducted by the appropriate personnel who would perform those tasks in a clinical setting.

Some institutions asked whether additional structures could be added to the scans to facilitate the production of the treatment plan. This is acceptable provided that only the dose statistics for the required structures are reported.

The detailed instruction sheets, data sheets and results reporting forms, as well as the specific nomenclature requirements that were prepared for the step 9 audit to specify the irradiation conditions and collect the necessary irradiation information (Package 12) are a part of the on-line supplementary files (which can be found on the publication's individual web page at www.iaea.org/publications).

5. CONCLUSION

One of the IAEA's goals is to provide services in the form of radiotherapy quality audits to Member States through the IAEA/WHO postal dose audit programme. Current estimates indicate that, of the 7000 radiotherapy centres worldwide that are identified in the IAEA's DIRAC database [7], only approximately two thirds of the facilities have participated in an independent dose quality audit [118]. Facilities not involved in external quality programmes may deliver inferior radiotherapy treatment due to inadequate dosimetry practices. One of the greatest risks for patients undergoing radiotherapy is that of inaccurate dose delivery, which can impact negatively on tumour control, treatment morbidity and normal tissue toxicity [9, 11–14, 20, 161, 162]. The primary objective of an external quality audit programme as developed by the IAEA is to ensure accurate dose delivery to radiotherapy patients. Differences between the dose prescribed and that delivered can directly impact on treatment outcomes. It is recognized internationally that an effective QA programme involves an independent dose assessment [9, 23, 51, 67, 163–165]. Every radiotherapy centre should have access to, and participate in, independent dosimetry audits, hence the need to have a guidance document such as this publication.

Thanks to these developments in the radiotherapy external audit systems at the international and national levels, as described in this report, better access to a QA audit programme is now available for many hospitals. The four IAEA radiotherapy QA audit CRPs developed an overall methodology for independent dosimetry audit in radiotherapy, where the philosophy was to begin with an audit of basic dosimetry, progressing to increasingly complex aspects of radiotherapy. The nine quality audit steps begin with a basic check of photon and electron beam outputs in reference conditions, and progress to an 'end-to-end' verification of advanced radiotherapy delivery found with IMRT and VMAT. These CRPs have developed concepts and frameworks for the establishment of DANs, through which the developing audits have been tested and disseminated at the national level in participating Member States. The various audit steps developed within the CRPs and described in this publication outline a robust, remote QA audit programme that can assist a radiotherapy centre in checking and ensuring delivery of accurate and safe radiation treatments. The mailed systems mostly help to detect and correct fundamental problems in basic dosimetry, which can be followed up on and corrected.

It is vital for hospitals to participate regularly in dosimetry audits. The experience and results from various DANs that have implemented these quality audit steps have shown that discrepancies are regularly discovered in the radiotherapy centres. The discovery of discrepancies allows for the analysis and resolution of any potential problem that might affect the quality of patient treatments. This publication serves as a concise, yet detailed, description of the need for a radiotherapy quality audit programme, how to establish a DAN and the nine quality audit steps developed to date.

Each of the quality audit steps outlined in this publication built upon the experience gained from the preceding audit step, from basic output checks to advanced radiotherapy dose delivery and 'end-to-end' checks. Regardless of the complexity, the vast majority of the audit steps rely on TLD and/or radiochromic film dosimetry processes developed by the IAEA. The success of this quality audit programme, evidenced by the extent of the audit procedures implemented throughout the world and the number of discrepancies discovered and resolved, merits continuation to ensure quality radiotherapy treatments in the range of Member States involved, with the potential to expand to others.

Through the continuing efforts of the IAEA to develop guidance documents like this publication, QA programmes can be further developed to assist Member States to provide accurate and safe radiotherapy treatments to a growing population of cancer patients. Continued development of QA programmes is particularly important as radiotherapy, a technology driven field, continues to evolve in technology and treatment technique complexity.

Appendix I

CHARACTERISTICS OF TLD SYSTEMS OF DOSIMETRY AUDIT CENTRES

The DACs typically use TLDs similar to those used for many years by the IAEA/WHO TLD postal dose audit programme [38, 66, 69, 70, 104, 107, 133]. Dosimeters consist of approximately 160 mg of LiF powder filled into capsules made of polyethylene. TLD system calibration is performed through irradiation of reference dosimeters in ^{60}Co gamma rays with the dose of 2 Gy. To determine the dose from the user dosimeter readings, several additional correction factors are applied [87, 166]. To ensure consistent high-quality operation of the system, verification of the TLD calibration at every reading session is performed. In addition, the dose response and fading function verification is done during the commissioning of every new lot of powder. IAEA Dosimetry Laboratory can provide several types of reference irradiations to organize external quality check. Some participants in CRPs E2.40.07 and E2.40.12 (Algeria, Argentina, Bulgaria, China, Cuba, India and Poland) submitted calibration data for their TLD systems, which is used in this Appendix for illustration and comparison with the IAEA TLD system.

I.1. DETERMINATION OF THE ABSORBED DOSE FROM TL READINGS

The absorbed dose to water, D_w, is calculated from the integrated TL response registered by the TLD reader using the formula:

$$D_w = M \cdot N \cdot f_{lin} \cdot f_{engy} \cdot f_{fad} \cdot f_{hol} \quad (4)$$

where

M [counts] is the TL response of the standard mass of LiF powder corrected for the reader's daily fluctuations by using the sensitivity drift correction factor;

N [Gy/counts] is the calibration coefficient of the TLD system and is defined as the inverse of the TL response per unit dose to water; N is determined for 2 Gy from a ^{60}Co beam;

f_{lin} is the non-linearity dose–response correction factor;

f_{engy} is the energy correction factor;

f_{fad} is the fading correction factor;

f_{hol} is the TLD holder correction factor.

The flow chart in Fig. 72 shows the steps required in the determination of absorbed dose to water from the TL response.

I.1.1. Calibration coefficient, *N*

For the determination of the calibration coefficient of the TLD system it is required to irradiate the TLD capsules in a water phantom or in an equivalent solid phantom in the reference conditions (10 × 10 cm^2 field size, at the usual SSD, i.e. SSD or source to dosimeter distance, at the reference depth of 5 cm or 10 cm) with 2 Gy in a ^{60}Co beam. Before irradiating the capsules, the absorbed dose to water

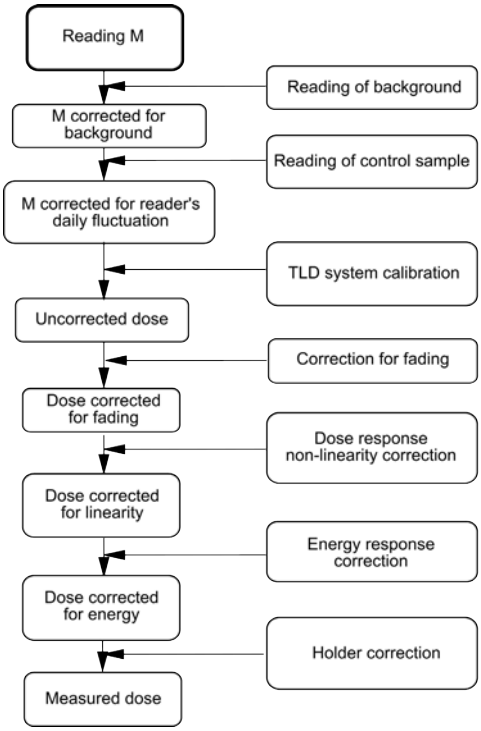


FIG. 72. Flow chart for the dose calculation from the TL readings.

has to be determined from the measurements with an IC placed at the depth of the TL detector centre. Dose to water at the position of the TL detector is calculated using the national dosimetry protocol or the recommended TRS-398 IAEA code of practice [109]. The system calibration factor N remains constant for all TLD samples from the same commissioned batch, but it can change with each readout due to possible changes in the batch sensitivity, the electronics and optics of the reader, the heater reflectivity, fluctuations in the heating temperature, and so on. Therefore, during each readout session it is advised to check the constancy of N using the reference TLD sample irradiated with ^{60}Co to the dose of 2 Gy in the usual reference conditions. The calibration coefficient N of the TLD system is determined for every new manufacturer's lot of TLD powder and repeated every 6 months, since the sensitivity of the TLD powder may vary after long term storage.

The calibration coefficient N is determined for 2 Gy from the response of n TLDs (e.g. n = 30) using the formula:

$$N = \frac{\sum_{i=1}^{n} \frac{D_i}{\left(M_i - \overline{B}\right)}}{n} \tag{5}$$

where $\overline{B}$ is the average background of the unexposed TLDs and M_i is the TL response of the i-th dosimeter irradiated with dose D_i as close as possible to 2 Gy.

I.1.2. Dose–response non-linearity correction, f_{lin}

LiF dose response exhibits a small supralinearity effect in the dose range of interest (for example, 2 Gy ± 1 Gy), which requires correction [167]. The non-linearity dose–response correction factor, $f_{\text{lin}}(D)$, has to be determined for every lot of TLD powder, together with the determination of the calibration coefficient.

The dose–response non-linearity correction factor is defined as the ratio of the TL response M_{D0} per unit dose measured at the dose D_0 = 2 Gy to the TL response M_D per unit dose measured at the dose D.

$$f_{\text{lin}} = \frac{\left[\frac{M_{D_0}}{D_0}\right]}{\left[\frac{M_D}{D}\right]} \tag{6}$$

The dose–response non-linearity correction factor, $f_{\text{lin}}(D)$, is determined by making a linear fit to the experimental data from the TL response per dose, as a function of dose, such that the fitted response per unit dose at the dose of 2 Gy equals 1 (the normalization point), as given in Eq. (7). The parameters of the non-linearity correction factor function, $f_{\text{lin}}(D)$, are derived from the linear fit to the experimental data:

$$f_{\text{lin}}(D) = a + b \cdot D \tag{7}$$

where a is the intercept of the least squares fit, b is the slope of the linearity correction ($a + 2b = 1$) and D is the dose to water at the position of the centre of the TLD capsule.

Examples of the dose–response non-linearity correction function obtained by the participants of the initial CRPs are given in Fig. 73(a), and the equivalent data for the IAEA system is shown in Fig. 73(b) for comparison. For every annealed lot of TLD powder, the dose responses have been studied, typically in the range 1.5–2.5 Gy. However, some TLD MCs have extended their studies of the non-linearity function to a range of doses from 0.5 to 3.0 Gy that was large enough to cover potential deviations in the dose by local hospitals. For each dose point, typically 5–6 TLD capsules have been irradiated and read out. Although the various TLD MCs use LiF:Mn,Ti powder by different manufacturers, their dose–response non-linearity correction functions are similar within the limit of the experimental uncertainty. The correction values range from 1.03 for 0.5 Gy to 0.97 for 3.0 Gy. Within the dose range from 1.5 to 2.5 Gy the correction is within ±1% (i.e. 1.01–0.99, respectively). The parameters of the dose–response non-linearity correction function averaged over all participants and fitting the global dose–response non-linearity correction, as given in Eq. (6), are a = 1.050 and b = –0.025 Gy^{-1}.

I.1.3. Energy correction, f_{engy}

The energy correction factor, f_{engy}, has to be applied to compensate for the changes in the TL response per unit dose with radiation beam energy. For photon beams, the TL response decreases with increasing energy, while for electron beams the effect is the reverse. The TLD response for a given dose depends on the beam energy, due to the dependence of the interaction coefficients of LiF on energy [168]. The energy correction factor for high energy photon or electron beams is defined as the ratio of the TL response M per unit dose measured at the dose D = 2 Gy in a ^{60}Co γ ray beam to the response M per unit dose at 2 Gy in the X ray beam of quality $\text{TPR}_{20,10}$ (where $\text{TPR}_{20,10}$ represents the tissue-phantom ratio in water at depths of 20 g/cm^2 and 10 g/cm^2, for a field size of 10 cm × 10 cm and a fixed source detector distance of 100 cm) or the electron beam of quality R_{50} (where R_{50} is the half-value depth in water (in g/cm^2)).

$$f_{\text{engy}} = \frac{\left[\frac{M}{D}\right]_{^{60}\text{Co}}}{\left[\frac{M}{D}\right]_{\text{X-ray/e}^-}} \tag{8}$$

The value of f_{engy} is determined by comparing the TLD response to the same dose to water in a high energy X ray or electron beam and a ^{60}Co beam, in the reference conditions. The absorbed dose to water in the centre of the TLD capsule for both beams is calculated from IC measurements in a water phantom. The dose is determined following the national dosimetry protocol or the IAEA TRS-398 [109] absorbed

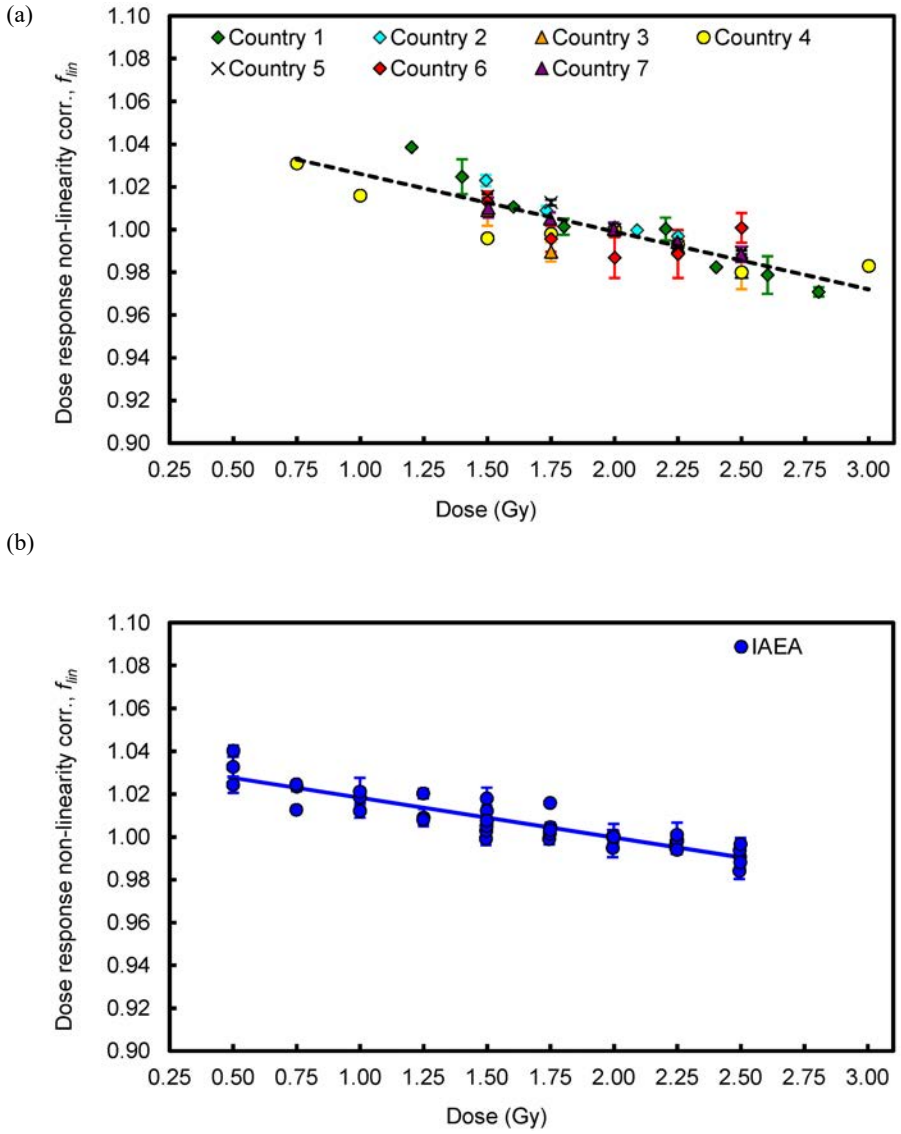


FIG. 73. The dose–response non-linearity correction function: (a) obtained by the different TLD MCs of the countries participating in the initial CRPs; (b) as used for the IAEA TLD measuring system.

dose to water based dosimetry code of practice. The values of the f_{engy} correction factor for the different beam qualities are approximated by a linear fit that is made to TL irradiations performed with these beams in the reference conditions.

The energy correction for high energy photon beams determined by the different TLD MCs is presented in Fig. 74(a) as provided by the CRP participant DANs, and in Fig. 74(b) as used in the IAEA system for comparison. The values exhibit a certain spread at the high energy region, depending on the LiF powder and TLD reading cycle used. The greatest f_{engy} correction, for $TPR_{20,10}$ values of 0.76–0.78, was 1.04–1.05 for LiF powders in countries 7 and 4, respectively, and the lowest correction of 1.03 was measured by country 2 for the Harshaw powder. The f_{engy} values measured by countries 1 and 6, using the Harshaw powder, were higher than those of country 2, but lower than those for countries 7 and 4 [169].

In general, a conclusion can be drawn, based on the individual sets of f_{engy} correction values determined by the different countries for high energy photon beams, that the energy correction for any LiF:Mg,Ti powder and any reading cycle would typically be within 1.03–1.05 for the highest photon beam energies as used clinically. These values are consistent with the f_{engy} used in the IAEA/WHO TLD postal dose audit system (Fig. 74(b)).

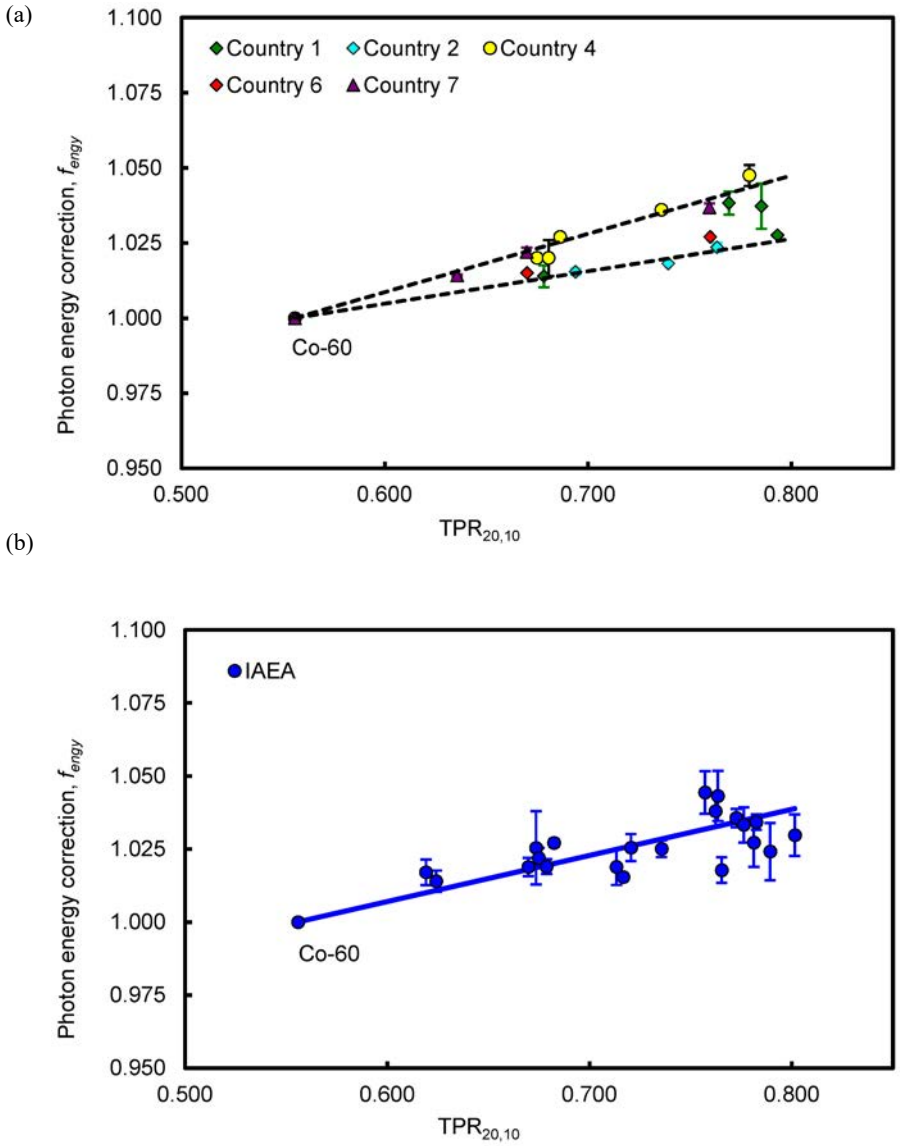


FIG. 74. The energy response correction for high energy photon beams: (a) determined by the different countries participating in the CRP; (b) as used for the IAEA system.

The energy correction for high energy electron beams measured by the different CRP participants is presented in Fig. 75. The values of the correction obtained by the individual centres all show a similar decreasing trend with the increasing electron beam energy. Typically, the difference in the correction between the lowest (2.3 g/cm^2 or 6 MeV) and the highest (8.7 g/cm^2 or 22 MeV) beam qualities is not greater than 2–3% for the individual countries; however, the lines are shifted in relation to one another. The differences may depend on individual differences in the geometry and set-up of the systems in the different countries. The values of f_{engy} compare favourably to those obtained by the Equal-Estro network, which also uses the IAEA standard TLD holders [72, 73].

It is advisable that the f_{engy} function is verified periodically (e.g. once a year) by analysing the responses of TLDs after irradiation in beams of different qualities.

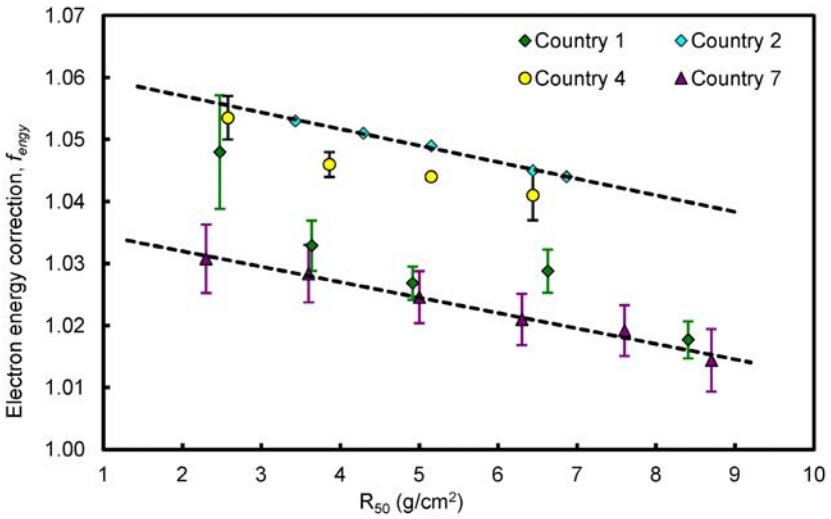


FIG. 75. The energy response correction for high energy electron beams determined by the different countries participating in the CRP.

I.1.4. Holder correction, f_{hol}

During an audit, TLDs are placed in the IAEA standard holder for irradiation. Different holders are used for photon and electron beams (Fig. 2 and Fig. 7). For electron beams the holder effect, if any, is included in the energy correction, f_{engy}, therefore no holder correction is used. For photon beams there is a 10 cm Perspex tube in front of the TLD capsule, partially covering the volume of the TLD, thus attenuating the beam and giving decreased TLD response. The holder correction factor is defined as the ratio of the TL response M of the powder irradiated in the capsule without the holder (subscript 'out') to that in the capsule placed in the holder (subscript 'in') with the same dose D = 2 Gy.

$$f_{\text{hol}} = \frac{\left[\frac{M}{D}\right]_{\text{out}}}{\left[\frac{M}{D}\right]_{\text{in}}} \tag{9}$$

The evaluation of the holder correction factors for photon beam qualities from ^{60}Co to 18 MV has previously been described (see Section 4.4.3 and [87, 106]). The decrease in the registered dose was found to be about 1% for ^{60}Co γ rays and a fraction of a per cent for high energy X rays for the TLD opening at 5 cm depth, and 1.8% for ^{60}Co beams and about 1% for 25 MV for the TLD at 10 cm depth. A linear function was fitted to the holder factor for both depths as a function of the beam quality.

I.1.5. Fading correction, f_{fad}

The TL signal fades with time after irradiation, mostly due to thermally induced release of trapped charges [168] in the TLD material after irradiation. Fading of the high temperature main dosimetric peaks (deep traps) of the glow curve of LiF is slow compared to unstable low temperature peaks (shallow traps), which have a half-life at room temperature of the order of a few days. This results in rapid TL response changes within 2–3 days after irradiation.

Even if a well-established annealing procedure reduces the relative magnitude of low temperature peaks and enhances the main dosimetric peaks, it is advisable to wait at least a few days after irradiation before reading out TLDs. Also, a post-irradiation or plateau preheating in the reader helps to reduce low temperature peaks and to stabilize the useful TL signal.

The fading function, $K_{fad}(\Delta t)$, is defined as the ratio of the TL response of a TLD irradiated on day t_1 and read on day t_2 to the response of a TLD irradiated on day t_1 and read after 7 days. The choice of normalizing the fading function to seventh day's TL reading is arbitrary and is appropriate considering the nature of the TLD services to radiotherapy centres, with typical time delays of weeks to months. The fading function is determined for each annealed batch of TLD powder and can be fitted with the expression

$$K_{\text{fad}}\left(\Delta t\right) = c + d \cdot \exp\left[-\left(t_2 - t_1 - 7\right)/f\right] \tag{10}$$

where c, d and f are coefficients obtained from the fit, which is done with the Levenberg–Marquardt algorithm for non-linear regression [170, 171].

A fading correction has to be applied to the TLD readings if the time elapsed between irradiation and readout differs for the participant and the reference TLDs. The fading correction $f_{fad}(\Delta t)$ is given by the expression

$$f_{\text{fad}} = \frac{K_{\text{fad}}\left(\Delta t_{\text{RD}}\right)}{K_{\text{fad}}\left(\Delta t_{\text{PD}}\right)} \tag{11}$$

or the ratio of the fading function for the reference dosimeter, RD, to the fading function for the participant dosimeter, PD; Δt_{RD} and Δt_{PD} are the time delays between the irradiation and the readout for the reference dosimeter and participant dosimeter, respectively.

Figure 76(a) shows examples of fading functions for the LiF powder determined by the participants of the CRPs with their TLD systems. Although the individual results are scattered, one can see that on average, the fading stabilizes at a level close to 97% approximately 100 days after the TLD irradiation. Between 100 and 200 days after TLD irradiation, only insignificant additional fading is observed. This result is consistent with the IAEA experience (Fig. 76(b)).

I.2. UNCERTAINTIES INVOLVED IN THE DOSE DETERMINATION FROM TLD READINGS

The combined standard uncertainty in the dose determined from TLD measurements is associated with the uncertainty in the determination of the absorbed dose to water in a ^{60}Co beam, where the reference TLDs are irradiated, and those uncertainties that are related to the TLD system. The evaluation of the uncertainties is based on the Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008, 2008) [172].

Assuming that the factors in Eq. (4) describing the determination of the dose from TLD measurements are uncorrelated, the combined relative standard uncertainty $u_c(D_{TLD})$ in the dose determined from the TLD measurements is the square root of the sum of the squared individual relative uncertainties:

$$u_c\left(D_{\text{TLD}}\right) = \sqrt{u\left(M\right)^2 + u\left(N\right)^2 + u\left(f_{\text{fad}}\right)^2 + u\left(f_{\text{hol}}\right)^2 + u\left(f_{\text{engy}}\right)^2 + u\left(f_{\text{lin}}\right)^2} \tag{12}$$

where $u(M)$ is the relative standard uncertainty in the mean reading of the TLD capsule, $u(N)$ is the relative standard uncertainty in the calibration coefficient, $u(f_{fad})$ is the relative standard uncertainty in the fading correction factor, $u(f_{hol})$ is the relative standard uncertainty in the TLD holder correction factor, $u(f_{engy})$ is the relative standard uncertainty in the energy correction factor and $u(f_{lin})$ is the relative standard uncertainty in the dose–response non-linearity correction factor.

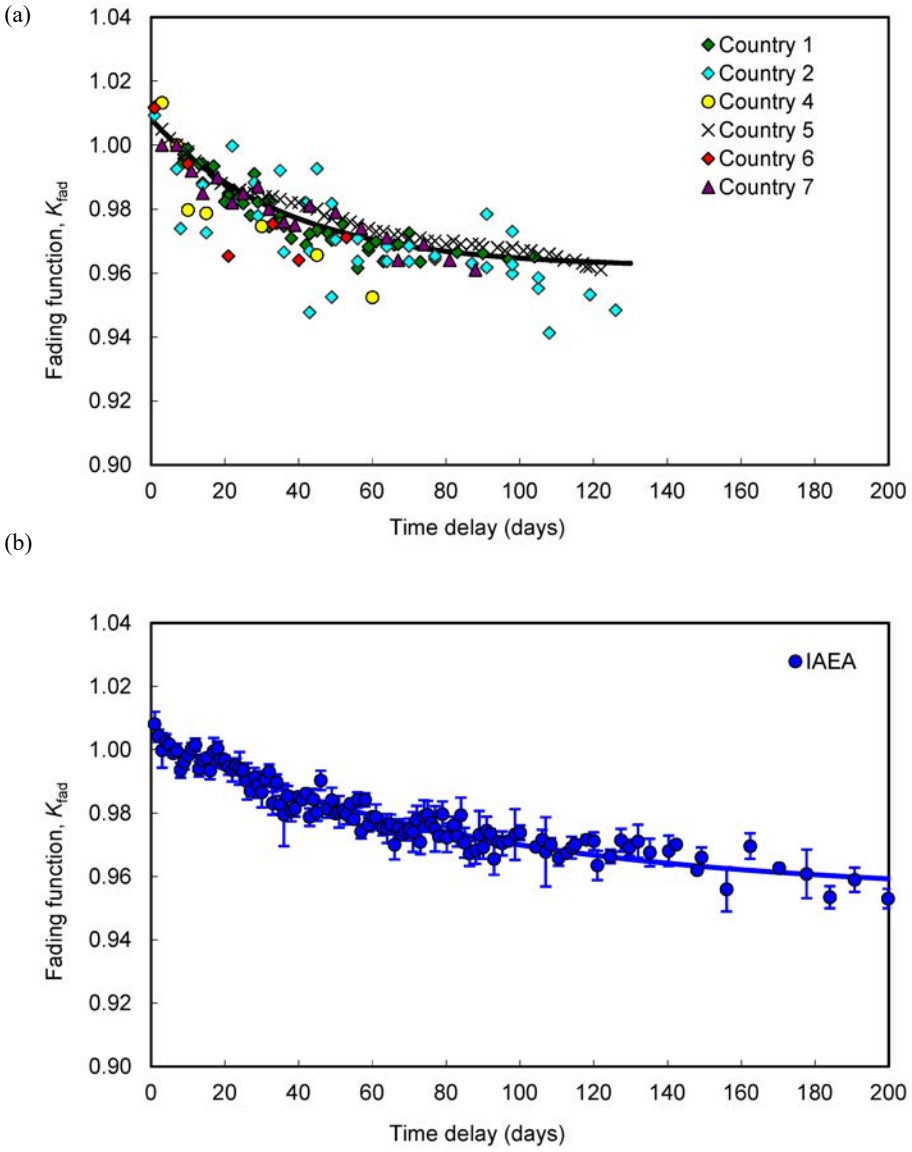


FIG. 76. Fading function measured for the LiF powder with different reading systems available in the TLD MCs. The fading function is normalized to the TLD response 7 days after irradiation. TLD powder was annealed following the procedure recommended by the manufacturer (e.g. 1 h at 400°C and 24 h at 80°C for Harshaw TLD-100 powder): (a) for the CRP participant DANs; (b) for the IAEA system.

I.2.1. Uncertainty in mean TLD reading, *u*(*M*)

The uncertainty in the mean TLD reading of a single capsule can be estimated as the arithmetic mean of the distribution of SDs of the mean for a large number of TLDs that have been irradiated with the same dose:

$$u(M) = \frac{\sum_i s_{M,i}}{l} = \frac{\sum_i s_i}{\sqrt{n} \cdot l} \tag{13}$$

where $s_{M,i}$ is the experimental SD of the mean reading of the *i*-th capsule, s_i is the SD of the readings of the *i*-th capsule, *n* is the number of readings per capsule and *l* is the total number of capsules in the distribution. The value of *l* needs to be large to get good statistics. The uncertainty described here is of type A.

The $u(M)$ uncertainty has been evaluated by individual DANs to the values in the range of 0.7% to 0.9%. Typically, 4–5 readings are taken from a TLD capsule.

I.2.2. Uncertainty in the calibration coefficient, $u(N)$

Reference capsules are irradiated in a ^{60}Co γ beam under the reference conditions. The uncertainty in the TLD calibration coefficient arises from the determination of the ^{60}Co dose, and the irradiation and reading of the TLD capsules. The combined relative uncertainty in the calibration coefficient is calculated as

$$u_c(N) = \sqrt{\frac{u(D_i)^2 + u(M_i)^2}{m}} = \sqrt{\frac{u(\dot{D})^2 + u(\text{irr})^2 + u(M_i)^2}{m}} \tag{14}$$

where $u(\dot{D})$is the relative uncertainty in the ^{60}Co dose rate, u(irr) the relative uncertainty in the irradiation of a TLD capsule, $u(M_i)$ the relative uncertainty $u(\dot{D})$ in the reading of a capsule and *m* is the number of capsules used for the determination of the TLD calibration coefficient *N*. Since the average background reading is many orders of magnitude smaller than the reading of a capsule, its contribution to the uncertainty is negligible.

The determination of the ^{60}Co dose rate to water is done from IC measurements following the IAEA TRS-398 code of practice [109]. The uncertainty $u(\dot{D})$ associated with the IC measurements in water originates mainly from the chamber calibration and the uncertainty in the chamber positioning, as well as the uncertainties related to the influence quantities, such as temperature and pressure. The uncertainties $u(\dot{D})$ in the calibration of the IC are of both type A and B. There is type A uncertainty in the correction of the stability of the IC and electrometer, type B uncertainty in the calibration of the voltmeter and capacitor, and type A and B uncertainties in the temperature and pressure measurements.

The uncertainties in the positioning of the chamber and phantom are of type B, and are estimated as the SD obtained from a rectangular distribution according to

$$\sigma = \frac{a}{\sqrt{3}} \tag{15}$$

where *a* is the half-width of the distribution. In the case of chamber positioning, the sensitivity coefficient, c_{cpos}, is obtained from the normalized depth dose curve that has been measured for the ^{60}Co unit and is equal to the dose gradient per millimetre at the depth of measurement (typically 5 cm). Thus, the uncertainty in the dose rate due to chamber positioning, $u(\dot{D})$, is

$$u_{\text{cpos}}(\dot{D}) = \left| c_{\text{cpos}} \bullet u(\text{cpos}) \right| \tag{16}$$

where $u_{\text{cpos}}(\dot{D})$ is the uncertainty in the chamber positioning obtained from the rectangular distribution according to Eq. (15).

Uncertainty in the irradiation, u(irr), of the TLDs arises from uncertainties in the positioning of the TLDs in the phantom and uncertainty in the timer of the ^{60}Co unit. The evaluation of the uncertainty in the positioning of the TLDs in the phantom is estimated from the rectangular distribution of the errors in positioning and follows the same procedure as with the positioning of the IC in the water phantom. The uncertainty in the TLD irradiation time is assumed to arise from the timer resolution. They are both of type B.

The evaluation of the type A uncertainty $u(M)$ in the mean TLD reading from one capsule is described in Section I.2.1.

Typical values of the combined relative uncertainty in the calibration coefficient $u_c(N)$ reported by DANs range from 1.0% to 1.8% per reference capsule. When two reference capsules are used in the TLD evaluation, the uncertainties $u_c(N)$ decrease to 0.7% and 1.3%, respectively. The major contribution to $u_c(N)$ is the uncertainty in the calibration coefficient of the IC used for ^{60}Co beam calibration. Lower uncertainties $u_c(N)$ have been reported in cases where IC measurements were performed with chambers calibrated in terms of absorbed dose to water, as compared to those calibrated in terms of air kerma. This is because of relatively large uncertainties in the interaction coefficients intrinsic to the air kerma based dosimetry protocols used for the determination of absorbed dose to water from IC measurements.

I.2.3. Uncertainty in the fading correction, $u(f_{\text{fad}})$

The uncertainty in the fading correction, $u(f_{\text{fad}})$, is a type A component and it is estimated as the mean of the distribution of the fading correction uncertainties for a large number of TLDs and time delays between the irradiation and readout of the DAN reference and the participant capsules.

The uncertainty in the fading correction is determined from error propagation according to

$$u\left(f_{\text{fad}}\right)=\sqrt{\left(\frac{\partial f_{\text{fad}}}{\partial c}\right)^2 u(c)^2+\left(\frac{\partial f_{\text{fad}}}{\partial d}\right)^2 u(d)^2+\left(\frac{\partial f_{\text{fad}}}{\partial f}\right)^2 u(f)^2} \tag{17}$$

where $u(c)$, $u(d)$ and $u(f)$ are the uncertainties in the coefficients c, d and f obtained from the non-linear regression. Including the partial derivatives, the variance becomes

$$\begin{aligned} u\left(f_{\text{fad}}\right)^2 &= \left(\frac{d\left[e^{-(t_{\text{P}}-7)/f}-e^{-(t_{\text{R}}-7)/f}\right]}{\left(K_{\text{fad}}^{\text{P}}\right)^2}\right)^2 u(c)^2+\left(\frac{d\left[e^{-(t_{\text{R}}-7)/f}-e^{-(t_{\text{P}}-7)/f}\right]}{\left(K_{\text{fad}}^{\text{P}}\right)^2}\right)^2 u(d)^2 \\ &+\left(\frac{cd\left[\left(t_{\text{R}}-7\right)e^{-(t_{\text{R}}-7)/f}-\left(t_{\text{P}}-7\right)e^{-(t_{\text{R}}-7)/f}\right]+d^2e^{-(t_{\text{R}}+t_P-14)/f}\left[t_{\text{R}}-t_{\text{P}}\right]}{f^2\left(K_{\text{fad}}^{\text{P}}\right)^2}\right)^2 u(f)^2 \end{aligned} \tag{18}$$

where t_{R} and t_{P} are the time delays between the irradiation and readout of the DAN reference and participant dosimeter, respectively.

The uncertainty in the fading correction is negligible for synchronized TLD runs, where hospital participants in the TLD audit run irradiate their TLDs at approximately the same time as the DANs irradiate reference TLDs that are later used in the TLD evaluation process.

I.2.4. Uncertainty in the holder correction, $u(f_{\text{hol}})$

The evaluation of the holder correction factor for beam qualities from ^{60}Co to 24 MV has previously been reported (Section 4.4.3 and [87, 106]). The relative standard uncertainty in the holder correction factor $u(f_{\text{hol}})$ is of type A and it was evaluated from the reproducibility of the measurements. The $u(f_{\text{hol}})$ uncertainty was estimated to be 0.3%.

I.2.5. Uncertainty in the energy correction, $u(f_{\text{engy}})$

The uncertainty in the energy correction is determined from the distribution of experimental results of the energy correction obtained from the dosimeters irradiated with different high energy photon and electron beams and normalized to the ^{60}Co response of TLDs. The uncertainty in the energy correction $u(f_{\text{engy}})$ is type A, evaluated by making a linear fit to the energy correction values obtained from responses of the TLDs and calculating the relative standard error of the estimate, according to the formula

$$u\left(f_{\text{engy}}\right)=\sqrt{\frac{\sum_{i}\left(f_{\text{fit},\,i}-f_{\text{meas},\,i}\right)^{2}}{K-2}} \tag{19}$$

where $f_{\text{fit},i}$ and $f_{\text{meas},i}$ are the fitted and measured correction values for the i-th dosimeter, respectively, and K is the number of dosimeters used in the fit [173]. The slope of the energy correction fit represents the mean value of the normally distributed variable with the standard error of the mean equal to the standard error of the regression coefficient. Typically, the values of $u(f_{\text{engy}})$ are of the order of 1.0%.

I.2.6. Uncertainty in the dose–response non-linearity correction, $u(f_{\text{lin}})$

The uncertainty in the dose–response non-linearity correction factor is determined similarly to that for the energy correction. A linear fit to experimental data is made from several TLD capsules irradiated with the various doses of the range from 0.5 Gy to 3 Gy in a few sessions, and the standard error of the estimate was calculated similarly to the method given in Eq. (19). Typical values of $u(f_{\text{lin}})$ are 1.0%–1.2%.

I.2.7. Combined relative standard uncertainty $u_c(D_{\text{TLD}})$ and $u_c(D_{\text{TLD}}/D_{\text{stat}})$

Table 26 presents an example of the relative standard uncertainties (1 SD in %) in the individual components in one of the DAN's TLD systems, contributing to the combined relative standard uncertainty in the dose determined from the TLD measurements. The individual components were obtained following the methodology described above. The combined relative standard uncertainty $u_c(D_{\text{TLD}})$ in the dose determined from the TLD measurements is the square root of the sum of the squared individual relative uncertainties (see Eq. (12)).

Major components in the uncertainty in the TLD calibration coefficient N are the uncertainty in the TLD reading of 0.70% and in the determination of the dose rate of the ^{60}Co beam at the country's SSDL of 0.61%. The largest contributors to the combined relative standard uncertainty have been found to be the energy correction factor f_{engy} for high energy X rays and the dose–response non-linearity correction factor f_{lin}, with uncertainties of 1.1% and 1.2%, respectively.

TABLE 26. RELATIVE STANDARD UNCERTAINTIES (1 SD IN %) IN THE INDIVIDUAL COMPONENTS AND THE COMBINED UNCERTAINTY IN THE DETERMINED DOSE

Component	Type A	Type B	Comb. A, B
M	0.70		0.70
N	0.71	0.64	0.96
f_{fad}	–		–
f_{hol}	0.30		0.30
f_{engy}*	1.10		1.10
f_{lin}	1.20		1.20
Co-60 beams	1.66	0.64	1.78
High energy X rays	1.91	0.64	2.01

* The uncertainty in the energy correction factor is not included in the combined uncertainty for Co-60 beams.

In the example above, the uncertainty in the fading correction factor has been omitted. In general, it is very small. It is minimized by irradiating the DAN's reference and the participant's TLDs as closely as possible in time. The detailed analysis of the uncertainty in the fading correction shows that its value is 0.02% for the IAEA TLD system [174]. The importance of the synchronization in TLD irradiation increases as the time delays between the irradiation and readout decrease. This is because the fading function has an exponential shape and its slope is greater for shorter delays between the irradiation and readout compared to long delays of more than 100 days, where the fading function stabilizes. Even so, the fading correction uncertainty gives only a minor contribution to the combined uncertainty.

Typically, the DAN TLD results certificate gives not only the values of the dose determined from TLD measurements but also the ratio of the TLD dose to that stated by the participant, D_{TLD}/D_{stat}. The uncertainty $u_c(D_{TLD}/D_{stat})$ depends on the uncertainty $u_c(D_{TLD})$ in the dose evaluated from the TLD measurements and on the uncertainty $u_c(D_{stat})$ in the dose given to the TLDs by the participant. The uncertainty $u_c(D_{TLD}/D_{stat})$ is equal to

$$u_c\left(\frac{D_{TLD}}{D_{stat}}\right)=\sqrt{\frac{u_c\left(D_{TLD}\right)^2+u_c\left(D_{stat}\right)^2}{L}} \tag{20}$$

where L is the number of TLDs used in the determination of the ratio. The average TL readings of two dosimeters are typically used by DANs for the determination of the dose from TLD measurements.

Appendix II

CHARACTERISTICS OF THE FILM DOSIMETRY SYSTEM

II.1. OVERVIEW

Radiochromic film is a challenging dosimeter but remains a staple for planar dosimetry in medical physics applications, and is the only currently viable planar detector for remote dosimetry audit programmes such as those discussed in this report. This Appendix serves as an overview of film handling and analysis guidelines. The aim of these guidelines are to achieve the optimal accuracy in film dosimetry, as well as to achieve standardized, and therefore comparable, results from different audits using film that are conducted by different groups. More comprehensive guides to film use are available in the literature, such as the AAPM TG-55 and the AAPM TG-235 reports [175, 176].

Film dosimetry cannot be separated from the scanner used to read the film. Choice of scanner is very important because it directly impacts on the management and use of film.

II.2. TYPES OF FILMS AND SCANNERS

While traditional radiographic silver halide films have a long history of use in medical physics applications, modern film dosimetry is done almost exclusively with radiochromic film because it obviates the need for wet chemical processing. There are many different types of radiochromic film currently available [176]. The audits described in this report were all developed and implemented with different types of EBT film (EBT2 for step 6 and EBT3 for the later steps). Any specific type of film that is implemented should be fully understood by the user [111–116].

There are a wide range of different types of scanners available for radiochromic film scanning. The most common type of scanner currently in use is the flatbed scanner. This type was used by the IAEA for its work in the audits conducted in this report (specifically an Epson 11000XL). Other scanners can be used successfully, although different scanner considerations are required for different scanners [177, 178]. Regardless of the scanner (or scanner type) used, it is important that the same scanner be used when scanning calibration films and experimental films.

II.3. DOSE–RESPONSE CHARACTERISTICS

The dose–response of film depends on the characteristics of the film and the radiation type used to irradiate the film, the dose level, the readout system and the time between irradiation and readout. A brief introduction to these items is given below.

Film type: The response of film depends on the manufacturer and model of film used, as different models of film have different lamination configurations and different absorption spectra because of their different compositions. However, even within the same model of film there can be substantial variations between different film batches (lot numbers). Therefore, it is important that calibration films and experimental films come from the same batch.

Radiation type: Most radiochromic films are designed to be nearly tissue equivalent and therefore have minimal energy dependence [110]. Because the energy dependence is less than 5% over the range of kV to MV photons and between photons and electrons, it is generally sufficient to establish and apply a calibration curve based on a single energy. However, for accurate dosimetry the film needs to be calibrated with the energy to be later used for measurements.

Dose level: The dose response of film is highly non-linear, necessitating an optical density (OD) to dose conversion that is obtained from the calibration curve. This OD–dose conversion is useful over a finite range of doses, providing increasingly less contrast as the dose increases. Different models of film have very different usable dose ranges; EBT3 film can be used over a dose range of approximately 0.2 Gy to 10 Gy.

Scanner properties: The nature of the scanner will affect the measured OD. The wavelength of the light source (and the response of the scanner detectors to that wavelength) affects the transmission through, which is why a consistent scanner needs to be used. For flatbed scanners, which can operate in transmission or reflection mode, choice of mode affects OD. More subtly, film orientation (i.e. landscape versus portrait) in the scanner affects OD measurement, and films should therefore all be scanned in the same orientation [112]. Lateral positions on flatbed scanners also have different sensitivities, and films need to all be positioned at the same place on the scanner when being scanned.

Time: After irradiation, radiochromic film continues to darken. This is most pronounced during the first few days, but continues over several weeks [175]. The timing between the irradiation of calibration films and the irradiation of experimental films need to therefore be managed. Ideally, the same amount of time should have elapsed between the irradiation of the calibration films and the irradiation of the experimental film(s). If that is not possible, a period of time (~24 hours) should be introduced between any irradiation and readout so that the most serious OD growth has passed. Other techniques have been proposed [113].

II.4. GENERAL FILM HANDLING

Radiochromic film needs to be stored in such a manner as to avoid accidental irradiation, heat (e.g. sunshine), exposure to UV light and excessive humidity. The film needs to be kept in a cool and dark location. Additionally, radiochromic film should not be handled with bare hands, as fingerprints and smudges will affect the OD upon scanning. Cotton gloves need to be worn when touching the film to avoid this. Finally, film needs not to be folded or damaged mechanically, as that will cause artefacts to appear when scanning irradiated films. Film needs to be carefully packaged for transport using rigid cardboard or similar material.

Film can be cut with a very sharp pair of scissors or other sharp cutting device. Because of mechanical damage to the film associated with it being cut, a 1 mm strip neighbouring the cut line is not usable for dosimetry purposes.

Because film has to be scanned in a consistent orientation in order to produce consistent results, it is important to mark (or otherwise preserve) the orientation of the cut pieces of film so that they can be scanned in the correct direction.

II.5. FILM CALIBRATION

In order to relate the OD of the film to dose, a calibration curve has to be established. The calibration curve has to be generated according to the film analysis software manufacturer's instructions over the dose range and beam energy relevant to the film application (and a dose level appropriate for the type of film used). For the audits discussed in this report, a calibration curve in 1 Gy steps from 0–10 Gy was constructed for each energy used in each corresponding audit step.

Once for each batch of film, a film calibration curve has to be generated. If film from a new batch is used, a new calibration curve has to be established and applied. A new calibration curve needs to be generated (even within the same batch) at least regularly enough that the currently applied curve remains valid.

II.6. SCANNING

While both transmission and reflection modes are possible for flatbed scanners, the effective dynamic range of the film is substantially reduced when reflection mode is used; transmission mode is therefore preferred when available. The scanner software (i.e. the software running the scan, not the software doing the gamma analysis) should not edit the image; image correction options should generally be disabled in this software to preserve the data on the film.

Before scanning any films, the scanner should be turned on for at least 30 min to warm up. The scanner light-source calibration area, marked on the scanner or ~1.5 cm of the glass window at the end where the scan starts, should be kept clean and otherwise free from interference. Films needs to be positioned in a consistent orientation and at a consistent position on the scanner (typically centred within the scanning area, along the central scanning axis). This consistency is particularly important between the calibration and experimental films. It is important that the films lay flat on the scanner bed because the film response varies with the distance between the film and light source [111, 114]. Ideally, the film should be covered with a 3–5 mm thick glass plate (that is free of defects) to avoid these problems; the glass size needs to be sufficient to cover the whole scanning area, i.e. the scanner plate. In lieu of a glass plate, adhesive tape can be used to keep the films flat on the scanner bed.

Once positioned, the film can be scanned. Three preview scans should be taken before the actual film scanning starts. Once scanned, the images need to be saved in a lossless format in order to preserve the image information, for example, using the .tiff format.

For the films used in this report, scanning was done on an Epson flatbed scanner in portrait orientation using the transmission mode, 72 dpi resolution and 48 bit colour scale (150 dpi for step 7b). The triple channel scanning approach was used.

II.7. ANALYSIS METHODS

A wide range of film analysis programmes are available and have been implemented in this audit. Unfortunately, there is substantial variability among the results produced by different film analysis programmes [103, 179]. This issue was more broadly evaluated specifically in the context of this audit programme, as detailed in Section 4.10.3. The percentage of pixels passing gamma was found to vary dramatically based on scanner/software combinations, and these differences were not consistent across the region of interest evaluated, gamma criteria selected or colour channel used. Even for a single film analysed by a single group, the percentage of pixels passing gamma was found to vary by up to 7% based on scanner and gamma parameter selection.

To minimize the variability in gamma results, it is essential to employ consistent analysis methods. For the audits implemented in this report, a standard was established of a 3%/3 mm gamma criteria evaluating all pixels above a 20% low dose threshold. More than 90% of pixels were required to pass these criteria.

Artefacts on the film, such as pinprick marks or areas within 1 mm of the cut edge of the film, should be excluded from analysis.

REFERENCES

[1] WORLD HEALTH ORGANIZATION, Global Cancer Observatory (2023), https://gco.iarc.fr/

[2] WORLD HEALTH ORGANIZATION, INTERNATIONAL UNION AGAINST CANCER, Global Action Against Cancer, World Health Organization and International Union Against Cancer, Switzerland (2005).

[3] STEWART, B.W., WILD, C.P. (Eds), World Cancer Report, IARC Press, Lyon (2014).

[4] FERLAY, J., et al., Estimates of worldwide burden of cancer in 2008: GLOBOCAN 2008, Int. J. Cancer **127** 12 (2010) 2893–2917.

[5] DELANEY, G., JACOB, S., FEATHERSTONE, C., BARTON, M., Radiotherapy in Cancer Care: Estimating optimal utilisation from a review of evidence based clinical guidelines, Collaboration for Cancer Outcomes Research and Evaluation (CCORE), Liverpool Hospital, Sydney (2003).

[6] NHS SCOTLAND, Cancer in Scotland: Radiotherapy Activity Planning 2011–15, Edinburgh (2005).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, DIRAC: Directory of radiotherapy centres (2018), https://dirac.iaea.org/

[8] ZUBIZARRETA, E.H., FIDAROVA, E., HEALY, B., ROSENBLATT, E., Need for radiotherapy in low and middle income countries — the silent crisis continues, Clin. Oncol. (R Coll Radiol) **27** 2 (2015) 107–114.

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Accuracy requirements and uncertainties in Radiotherapy, IAEA Human Health Series No. 31, IAEA, Vienna (2016).

[10] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, ICRU Report 24, Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures, ICRU, Bethesda, MD (1976).

[11] THWAITES, D.I., MIJNHEER, B., MILLS, J. "Quality assurance of external beam radiotherapy", Radiation Oncology Physics: A Handbook for Teachers and Students (PODGORSAK, E.B., Ed.), IAEA, Vienna (2005).

[12] VAN DYK, J., PURDY, J.A., "Clinical implementation of technology and the quality assurance process", The Modern Technology of Radiation Oncology: A Compendium for Medical Physicists and Radiation Oncologists, (ED, V. D. J., Ed.), Medical Physics Publishing, Madison, WI (1999).

[13] THWAITES, D.I., Accuracy required and achievable in radiotherapy dosimetry: Have modern technology and techniques changed our views? J. Phys. Conf. Ser. **444** (2013) 012006.

[14] MIJNHEER, B. (Ed.), Clinical 3D Dosimetry in Modern Radiation Therapy, CRC Press, Boca Raton, FL (2017).

[15] WORLD HEALTH ORGANIZATION, Quality Assurance in Radiotherapy, WHO, Geneva (1988).

[16] KUTCHER, G.J., et al., Comprehensive QA for radiation oncology: Report of AAPM Radiation Therapy Committee Task Group 40, Med. Phys. **21** 4 (1994) 581–618.

[17] LEER, J.W.H., McKENZIE, A. L., SCALLIET, P., THWAITES, D.I., Practical guidelines for the implementation of a Quality System in Radiotherapy, ESTRO recommendations, European Society for Therapeutic Radiology and Oncology, Brussels (1998).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Accidental Exposures in Radiotherapy, IAEA, Vienna (2000).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Oncology Physics: A Handbook for Teachers and Students, IAEA, Vienna (2005).

[20] MIJNHEER, B.J., BATTERMANN, J.J., WAMBERSIE, A., What degree of accuracy is required and can be achieved in photon and neutron therapy? Radiother. Oncol. **8** 3 (1987) 237–252.

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Comprehensive Audits of Radiotherapy Practices: A Tool for Quality Improvement - Quality Assurance Team for Radiation Oncology (QUATRO), IAEA, Vienna (2007).

[22] THWAITES, D., SCALLIET, P., LEER, J.W., OVERGAARD, J., Quality assurance in radiotherapy: European Society for Therapeutic Radiology and Oncology Advisory Report to the Commission of the European Union for the 'Europe Against Cancer Programme', Radiother. Oncol. **35** 1 (1995) 61–73.

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Applying Radiation Safety Standards in Radiotherapy, Safety Report Series No. 38, IAEA, Vienna (2006).

[24] EUROPEAN COMMISSION, Radiation Protection No. 159 European Commission guidelines on clinical audit for medical radiological practices (diagnostic radiology, nuclear medicine and radiotherapy), Publications Office of the European Union, Luxembourg (2009).

[25] MIFTEN, M., et al., Tolerance limits and methodologies for IMRT measurement-based verification QA: Recommendations of AAPM Task Group No. 218, Med. Phys. **45** 4 (2018) 53–83.
[26] BISSONNETTE, J.P., et al., Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179, Med. Phys. **39** 4 (2012) 1946–1963.
[27] DIETERICH, S., et al., Report of AAPM TG 135: Quality assurance for robotic radiosurgery, Med. Phys. **38** 6 (2011) 2914–2936.
[28] KLEIN, E. E., et al., Task Group 142 report: quality assurance of medical accelerators, Med. Phys. **36** 9 (2009) 4197–4212.
[29] DAS, I.J., et al., Accelerator beam data commissioning equipment and procedures: Report of the TG-106 of the Therapy Physics Committee of the AAPM, Med. Phys. **35** 9 (2008) 4186–4215.
[30] BENTZEN, S.M., et al., Towards evidence-based guidelines for radiotherapy infrastructure and staffing needs in Europe: the ESTRO QUARTS project, Radiother. Oncol. **75** 3 (2005) 355–365.
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Setting Up a Radiotherapy Programme: Clinical, Medical Physics, Radiation Protection and Safety Aspects, IAEA, Vienna (2008).
[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Staffing in Radiotherapy: An Activity Based Approach, IAEA Human Health Reports (CD-ROM) No. 13., IAEA, Vienna (2015).
[33] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Prevention of Accidental Exposures to Patients Undergoing Radiation Therapy, ICRP Publication No. 86, Pergamon Press, Oxford and New York (2000).
[34] AMERICAN SOCIETY FOR RADIATION ONCOLOGY, Safety is No Accident: A Framework for Quality Radiation Oncology and Care, ASTRO, (2012).
[35] WORLD HEALTH ORGANIZATION, Radiotherapy Risk Profile: Technical Manual, WHO, Geneva (2008).
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Investigation of an Accidental Exposure of Radiotherapy Patients in Panama - Report of a Team of Experts, 26 May–1 June 2001, IAEA, Vienna (2001).
[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Accidental Overexposure of Radiotherapy Patients in Bialystok, IAEA, Vienna (2004).
[38] IZEWSKA, J., ANDREO, P., VATNITSKY, S., SHORTT, K.R., The IAEA/WHO TLD postal dose quality audits for radiotherapy: a perspective of dosimetry practices at hospitals in developing countries, Radiother. Oncol. **69** 1 (2003) 91–97.
[39] DUTREIX, A., DERREUMAUX, S., CHAVAUDRA, J., VAN DER SCHUEREN, E., Quality control of radiotherapy centres in Europe: beam calibration, Radiother. Oncol. **32** 3 (1994) 256–264.
[40] KRY, S.F., et al., Radiation therapy deficiencies identified during on-site dosimetry visits by the imaging and radiation oncology core houston quality assurance center, Int. J. Radiat. Oncol. Biol. Phys. **99** 5 (2017) 1094–1100.
[41] CARSON, M.E., et al., Examining credentialing criteria and poor performance indicators for IROC Houston's anthropomorphic head and neck phantom, Med. Phys. **43** 12 (2016) 6491–6496.
[42] GERSHKEVITSH, E., et al., Dosimetric inter-institutional comparison in European radiotherapy centres: Results of IAEA supported treatment planning system audit, Acta Oncol. **53** 5 (2014) 628–636.
[43] KRY, S., et al., Remote beam output audits: A global assessment of results out of tolerance, Phys. Imag. Radiat. Oncol. **7** 2018 (2018) 39–44.
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, On-site Visits to Radiotherapy Centres: Medical Physics Procedures - Quality Assurance Team for Radiation Oncology (QUATRO), IAEA, Vienna (2007).
[45] HUQ, M.S., et al., The report of Task Group 100 of the AAPM: Application of risk analysis methods to radiation therapy quality management, Med. Phys. **43** 7 (2016) 4209–4262.
[46] WEXLER, A., et al., FMEA of manual and automated methods for commissioning a radiotherapy treatment planning system, Med. Phys. **44** 9 (2017) 4415–4425.
[47] POTTERS, L., FORD, E., EVANS, S., PAWLICKI, T., MUTIC, S., A systems approach using big data to improve safety and quality in radiation oncology, Int. J. Radiat. Oncol. Biol. Phys. **95** 3 (2016) 885–889.
[48] PAWLICKI, T., et al., Application of systems and control theory-based hazard analysis to radiation oncology, Med. Phys. **43** 3 (2016) 1514–1530.
[49] MANGER, R.P., PAXTON, A.B., PAWLICKI, T., KIM, G.Y., Failure mode and effects analysis and fault tree analysis of surface image guided cranial radiosurgery, Med. Phys. **42** 5 (2015) 2449–2461.
[50] PAWLICKI, T., CHERA, B., NING, T., MARKS, L.B., The systematic application of quality measures and process control in clinical radiation oncology, Semin Radiat Oncol **22** 1 (2012) 70–76.
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
[52] IZEWSKA, J., THWAITES, D.I., "IAEA supported national thermoluminescence dosimetry audit networks for

radiotherapy dosimetry", Standards and Codes of Practice in Medical Radiation Dosimetry: Proc. of the Int. Symp. 2002, IAEA, Vienna (2002).
[53] DUTREIX A., HANSON W.F., JARVINEN H., JOHANSSON K.A., THWAITES T., "Recommendations for an independent verification of the initial output calibration of megavoltage radiotherapy unit", Radiation dose in radiotherapy from prescription to delivery. Proceedings of the Interregional Seminar for Europe, the Middle East and Africa organised by the IAEA/ESTRO, Leuven, 16–20 Sept. 1991, IAEA, Vienna (1994).
[54] IZEWSKA, J., et al., Improving the quality of radiation oncology: 10 years' experience of QUATRO audits in the IAEA Europe Region, Radiother. Oncol. **126** 2 (2018) 183–190.
[55] JURADO-BRUGGEMAN, D., et al., Multi-centre audit of VMAT planning and pre-treatment verification, Radiother. Oncol. **124** 2 (2017) 302–310.
[56] CLARK, C.H., HURKMANS, C.W., KRY, S.F., GLOBAL QUALITY ASSURANCE OF RADIATION THERAPY CLINICAL TRIALS HARMONISATION GROUP, The role of dosimetry audit in lung SBRT multi-centre clinical trials, Phys. Med. **44** (2017) 171–176.
[57] VAN DER MERWE, D., et al., Accuracy Requirements and Uncertainties in Radiotherapy: A Report of the International Atomic Energy Agency, Acta Oncol. **56** 1 (2017) 1–6.
[58] IZEWSKA, J., et al., Testing the methodology for dosimetry audit of heterogeneity corrections and small MLC-shaped fields: Results of IAEA multi-center studies, Acta Oncol. **55** 7 (2016) 909–916.
[59] CLARK, C.H., et al., Radiotherapy dosimetry audit: three decades of improving standards and accuracy in UK clinical practice and trials, Br. J. Radiol. **88** 1055 (2015) 20150251.
[60] MIRI, N., et al., Remote dosimetric auditing for intensity modulated radiotherapy: A pilot study, Phys. Imag. Radiat. Oncol. **4** (2017) 26–31.
[61] LEHMANN, J., et al., Dosimetric end-to-end tests in a national audit of 3D conformal radiotherapy, Phys. Imag. Radiat. Oncol. **6** (2018) 5–11.
[62] HUMBERT-VIDAN, L., SANDER, T., EATON, D.J., CLARK, C.H., National audit of a system for rectal contact brachytherapy, Phys. Imag. Radiat. Oncol. **1** (2017) 1–5.
[63] IZEWSKA, J., LECHNER, W., WESOLOWSKA, P., Global availability of dosimetry audits in radiotherapy: The IAEA dosimetry audit networks database, Phys. Imag. Radiat. Oncol. **5** (2018) 1–4.
[64] PASLER, M., HERNANDEZ, V., JORNET, N., CLARK, C.H., Novel methodologies for dosimetry audits: Adapting to advanced radiotherapy techniques, Phys. Imag. Radiat. Oncol. **5** (2018) 76–84.
[65] LECHNER, W., et al., A multinational audit of small field output factors calculated by treatment planning systems used in radiotherapy, Phys. Imag. Radiat. Oncol. **5** 2018 (2018) 58–63.
[66] INTERNATIONAL ATOMIC ENERGY AGENCY, SSDL Newsletter No. 58, IAEA, Vienna (2010).
[67] EUROPEAN UNION, Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, Official Journal of the European Union, **No. L 13/1** 2013 (2013)
[68] INTERNATIONAL ATOMIC ENERGY AGENCY, SSDL Newsletter No. 70, IAEA, Vienna (2019).
[69] SVENSSON, H., HANSON, G.P., ZSDANSZKY, K., The IAEA/WHO TL dosimetry service for radiotherapy centres 1969–87, Acta Oncol. **29** 4 (1990) 461–467.
[70] IZEWSKA, J., ANDREO, P., The IAEA/WHO TLD postal programme for radiotherapy hospitals, Radiother. Oncol. **54** 1 (2000) 65–72.
[71] IBBOTT, G., NELSON, A., FOLLOWILL, D., BALTER, P., HANSON, W.F., "An anthropomorphic head and neck phantom for the evaluation of intensity modulated radiation therapy", Standards and Codes of Practice in Medical Radiation Dosimetry: Proc. of the Internationa Symposium on 25–28 November 2002, IAEA, Vienna (2003).
[72] ROUE, A., VAN DAM, J., DUTREIX, A., SVENSSON, H., The EQUAL-ESTRO external quality control laboratory in France, Cancer Radiother. **8** Suppl. 1 (2004) S44–49.
[73] FERREIRA, I.H., DUTREIX, A., BRIDIER, A., SVENSSON, H., ESTRO European assurance programme for radiation treatments (the EQUAL network), Standards and Codes of Practice in Medical Radiation Dosimetry: Proc. of an International Symposium on 25–28 November 2002, Vienna (2002).
[74] AGUIRRE, J. F., TAILOR, R.C., IBBOTT, G., STOVALL, M., HANSON, W.F., "Thermoluminescence dosimetry as a tool for the remote verification of output for radiotherapy beams: 25 years of experience", Standards and Codes of Practice in Medical Radiation Dosimetry: Proceeding of the International Symposium on 25–28 November 2002, IAEA, Vienna (2003).
[75] MOLINEU, A., et al., Design and implementation of an anthropomorphic quality assurance phantom for

intensity-modulated radiation therapy for the Radiation Therapy Oncology Group, Int. J. Radiat. Oncol. Biol. Phys. **63** 2 (2005) 577–583.
[76] HANSON, W.F., SHALEK, R.J., KENNEDY, P., Dosimetry quality assurance in the U.S. from the experience of the Radiological Physics Center, SSDL Newsletter No. 30, IAEA, Vienna (1991).
[77] ALVAREZ, P., KRY, S.F., STINGO, F., FOLLOWILL, D., TLD and OSLD dosimetry systems for remote audits of radiotherapy external beam calibration, Radiat. Meas. **106** (2017) 412–415.
[78] KRY, S. F., et al., Institutional patient-specific IMRT QA does not predict unacceptable plan delivery, Int. J. Radiat. Oncol. Biol. Phys. **90** 5 (2014) 1195–1201.
[79] MCKENZIE, E.M., et al., Toward optimizing patient-specific IMRT QA techniques in the accurate detection of dosimetrically acceptable and unacceptable patient plans, Med. Phys. **41** 12 (2014).
[80] INTERNATIONAL ATOMIC ENERGY AGENCY, Dosimetry Audit Networks (DAN) database (2019), https://dosimetry-audit-networks.iaea.org/
[81] KRON, T., HAMILTON, C., ROFF, M., DENHAM, J., Dosimetric intercomparison for two Australasian clinical trials using an anthropomorphic phantom, Int. J. Radiat. Oncol. Biol. Phys. **52** 2 (2002) 566–579.
[82] KROUTILKKOVA, D., NOVOTNY, J., JUDAS, L., Thermoluminescent dosimeters (TLD) quality assurance network in the Czech Republic, Radiother. Oncol. **66** 2 (2003) 235–244.
[83] FERREIRA, I., et al., "Radiotherapy dosimetry audit; a European programme to improve quality and safety in radiation treatments", Radiological protection of patients in diagnostic and interventional radiology, nuclear medicine and radiotherapy: Proc. Int. Conf. Málaga 2001, IAEA, Vienna (2001).
[84] PYCHLAU, C., A radiation therapy TLD service in Germany: The experience of the first year, Standard and Codes of Practice in Medical Radiaion Dosimetry: Proc. of an Int. Symp. 2002, IAEA, Vienna (2002).
[85] BULSKI, W., CHELMINSKI, K., ROSTKOWSKA, J., Dosimetry audit of radiotherapy treatment planning systems, Radiat Prot Dosimetry **165** 1–4 (2015) 472–476.
[86] KIRBY, T.H., HANSON, W.F., JOHNSTON, D.A., Uncertainty analysis of absorbed dose calculations from thermoluminescence dosimeters, Med. Phys. **19** 6 (1992) 1427–1433.
[87] IZEWSKA, J., NOVOTNY, J., VAN DAM, J., DUTREIX, A., VAN DER SCHUEREN, E., The influence of the IAEA standard holder on dose evaluated from TLD samples, Phys. Med. Biol. **41** 3 (1996) 465–473.
[88] NYSTRÖM, H., BERA, P., NETTE, P., "Beam quality dependence of the IAEA TL-dosimeters in a standardised geometry", Measurement Assurance in Dosimetry, Proc. of a Symp. Vienna 1993, IAEA, Vienna (1994).
[89] WESOLOWSKA, P.E., et al., Characterization of three solid state dosimetry systems for use in high energy photon dosimetry audits in radiotherapy, Radiation Measurements **106** (2017) 556–562.
[90] MIZUNO, H., et al., Application of a radiophotoluminescent glass dosimeter to nonreference condition dosimetry in the postal dose audit system, Med. Phys. **41** 11 (2014).
[91] MIZUNO, H., et al., Feasibility study of glass dosimeter postal dosimetry audit of high-energy radiotherapy photon beams, Radiother. Oncol. **86** 2 (2008) 258–263.
[92] DIMITRIADIS, A., PALMER, A.L., THOMAS, R.A.S., NISBET, A., CLARK, C.H., Adaptation and validation of a commercial head phantom for cranial radiosurgery dosimetry end-to-end audit, Br. J. Radiol. **90** 1074 (2017).
[93] DE OST, B., SCHAEKEN, B., VYNCKIER, S., STERPIN, E., VAN DEN WEYNGAERT, D., Reference dosimetry for helical tomotherapy: practical implementation and a multicenter validation, Med. Phys. **38** 11 (2011) 6020–6026.
[94] BUDGELL, G., et al., A national dosimetric audit of IMRT, Radiother. Oncol. **99** 2 (2011) 246–252.
[95] SCHAEKEN, B., et al., Implementation of alanine/EPR as transfer dosimetry system in a radiotherapy audit programme in Belgium, Radiother. Oncol. **99** 1 (2011) 94–96.
[96] SHARPE, P.H.G., RAJENDRAN, K., SEPHTON, J.P., Progress towards an alanine/ESR therapy level reference dosimetry service at NPL, Appl. Radiat. Isotopes. **47** 11–12 (1996) 1171–1175.
[97] BRIDIER, A., NYSTROM, H., FERREIRA, I., GOMOLA, I., HUYSKENS, D., A comparative description of three multipurpose phantoms (MPP) for external audits of photon beams in radiotherapy: the water MPP, the Umea MPP and the EC MPP, Radiother. Oncol. **55** 3 (2000) 285–293.
[98] MOLINEAU, A., HERNANDEZ, N., NGUYEN, T., IBBOTT, G., FOLLOWILL, D., Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom, Med. Phys. **40** (2013).
[99] KRY, S.F., et al., Algorithms used in heterogeneous dose calculations show systematic differences as measured with the Radiological Physics Center's anthropomorphic thorax phantom used for RTOG credentialing, Int. J. Radiat. Oncol. Biol. Phys. **85** 1 (2013) E95–E100.
[100] KRY, S.F., JONES, J., CHILDRESS, N.L., Implementation and evaluation of an end-to-end IGRT test, J. Appl. Clin. Med. Phys. **13** 5 (2012) 46–53.

[101] MOLINEU, A., HERNANDEZ, N., NGUYEN, T., IBBOTT, G., FOLLOWILL, D., Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom, Med. Phys. **40** 2 (2013).
[102] GLOBAL QUALITY ASSURANCE OF RADIATION THERAPY CLINICAL TRIALS HARMONISATION GROUP, https://rtqaharmonization.org/
[103] HUSSEIN, M., et al., GLOBAL QUALITY ASSURANCE OF RADIATION THERAPY CLINICAL TRIAL HARMONISATION GROUP. A virtual dosimetry audit - Towards transferability of gamma index analysis between clinical trial QA groups, Radiother. Oncol. **125** 3 (2017) 398–404.
[104] IZEWSKA, J., et al., Guidelines for the preparation of a quality manual for external audit groups on dosimetry in radiotherapy, SSDL Newsletter No. 46, IAEA/WHO, Vienna (2002).
[105] WESOLOWSKA, P., et al., Testing the methodology for a dosimetric end-to-end audit of IMRT/VMAT: results of IAEA multicentre and national studies, Acta Oncol. **58** 12 (2019) 1731–1739.
[106] IZEWSKA, J., et al., A methodology for TLD postal dosimetry audit of high-energy radiotherapy photon beams in non-reference conditions, Radiother. Oncol. **84** 1 (2007) 67–74.
[107] IZEWSKA, J., SVENSSON, H., IBBOTT, G., "Worldwide quality assurance networks for radiotherapy dosimetry", Standards and Codes of Practice in Medical Radiation Dosimetry: Proc. of the Int. Symp. 2002, IAEA, Vienna (2002).
[108] GOMOLA, I., et al., External audits of electron beams using mailed TLD dosimetry: preliminary results, Radiother. Oncol. **58** 2 (2001) 163–168.
[109] INTERNATIONAL ATOMIC ENERGY AGENCY, Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water, Technical Report Series No. 398, IAEA, Vienna (2000).
[110] BEKERAT, H., et al., Improving the energy response of external beam therapy (EBT) GafChromicTM dosimetry films at low energies (≤ 100 keV), Med. Phys. **41** 2 (2014) 022101.
[111] LEWIS, D., MICKE, A., YU, X., CHAN, M.F., An efficient protocol for radiochromic film dosimetry combining calibration and measurement in a single scan, Med. Phys. **39** 10 (2012) 6339–6350.
[112] BUTSON, M.J., CHEUNG, T., YU, P.K., Scanning orientation effects on Gafchromic EBT film dosimetry, Australas Phys. Eng. Sci. Med. **29** 3 (2006) 281–284.
[113] LEWIS, D., DEVIC, S., Correcting scan-to-scan response variability for a radiochromic film-based reference dosimetry system, Med. Phys. **42** 10 (2015) 5692–5701.
[114] PALMER, A.L., BRADLEY, D.A., NISBET, A., Evaluation and mitigation of potential errors in radiochromic film dosimetry due to film curvature at scanning, J. Appl. Clin. Med. Phys. **16** 2 (2015) 425–431.
[115] DREINDL, R., GEORG, D., STOCK, M., Radiochromic film dosimetry: considerations on precision and accuracy for EBT2 and EBT3 type films, Z. Med. Phys. **24** 2 (2014) 153–163.
[116] FUSS, M., STURTEWAGEN, E., DE WAGTER, C., GEORG, D., Dosimetric characterization of GafChromic EBT film and its implication on film dosimetry quality assurance, Phys. Med. Biol. **52** 14 (2007) 4211–4225.
[117] IZEWSKA, J., Setting up a dosimetry audit centre: infrastructure and resources, SSDL Newsletter No. 66, IAEA, Vienna (2016).
[118] GROCHOWSKA, P., IZEWSKA, J., An IAEA survey of dosimetry audit networks for radiotherapy, SSDL Newsletter No. 61, IAEA, Vienna (2013).
[119] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories ISO/IEC 17025, ISO, Geneva (2005).
[120] ALMOND, P.R., et al., AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams, Med. Phys. **26** 9 (1999) 1847–1870.
[121] INTERNATIONAL ATOMIC ENERGY AGENCY, Dosimetry of Small Static Fields Used in External Beam Radiotherapy, Technical Reports Series No. 483, IAEA, Vienna (2017).
[122] LYE, J., et al., A 2D ion chamber array audit of wedged and asymmetric fields in an inhomogeneous lung phantom, Med. Phys. **41** 10 (2014).
[123] EZZELL, G.A., et al., IMRT commissioning: multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119, Med. Phys. **36** 11 (2009) 5359–5373.
[124] MIJNHEER, B., GEORG, D., (Eds), Guidelines for the Verification of IMRT, European Guidelines for Quality Assurance in Radiotherapy, ESTRO Booklet Series No. 9 (Guidelines for the verification of IMRT) ESTRO, Brussels (2008).
[125] KARLSSON, M., AHNESJÖ, A., GEORG, D., OLOFSSON, J., NYHOLM, T., Independent dose calculations—concepts and models, ESTRO Booklet Series, No. 10, ESTRO, Brussels (2010).

[126] IZEWSKA, J., The IAEA methodologies for 'end-to-end' on-site audits, SSDL Newsletter No. 70, IAEA/WHO, Vienna (2019).
[127] LOPES. M.C., SANTOS. T., Dosimetry audits – the Portuguese experience, SSDL Newsletter No. 70, IAEA/WHO, Vienna (2019).
[128] SANTOS, T., et al., IMRT national audit in Portugal, Phys. Med. **65** 2019 (2019) 128–136.
[129] MURPHY, M.J., et al., The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75, Med. Phys. **34** 10 (2007) 4041–4063.
[130] STOCK, M., PALM, A., ALTENDORFER, A., STEINER, E., GEORG, D., IGRT induced dose burden for a variety of imaging protocols at two different anatomical sites, Radiother. Oncol. **102** 3 (2012) 355–363.
[131] IZEWSKA, J., THWAITES, D.I., "IAEA supported national thermoluminescence dosimetry audit networks for radiotherapy dosimetry", Standards and Codes of Practice in Medical Radiation Dosimetry: Proc. of the Int. Symp. 2002, IAEA, Vienna (2002).
[132] IZEWSKA, J., et al., Quality assurance network in Central Europe: External audit on output calibration for photon beams, Acta Oncol. **34** 6 (1995) 829–838.
[133] IZEWSKA, J., BERA, P., VATNITSKY, S., IAEA/WHO TLD postal dose audit service and high precision measurements for radiotherapy level dosimetry Radiat. Prot. Dos. **101** 1–4 (2002) 387–392.
[134] BARTOLOTTA, A., et al., The response behaviour of LiF:Mg,Cu,P thermoluminescence dosimeters to high-energy electron beams used in radiotherapy, Phys. Med. Biol. **40** 2 (1995) 211–220.
[135] KNOOS, T., AHNESJO, A., NILSSON, P., WEBER, L., Limitations of a pencil beam approach to photon dose calculations in lung tissue, Phys. Med. Biol. **40** 9 (1995) 1411–1420.
[136] KNOOS, T., et al., Comparison of dose calculation algorithms for treatment planning in external photon beam therapy for clinical situations, Phys. Med. Biol. **51** 22 (2006) 5785–5807.
[137] AHNESJO, A., Collapsed cone convolution of radiant energy for photon dose calculation in heterogeneous media, Med. Phys. **16** 4 (1989) 577–592.
[138] CARRASCO, P., et al., Comparison of dose calculation algorithms in phantoms with lung equivalent heterogeneities under conditions of lateral electronic disequilibrium, Med. Phys. **31** 10 (2004) 2899–2911.
[139] AARUP, L.R., et al., The effect of different lung densities on the accuracy of various radiotherapy dose calculation methods: Implications for tumour coverage, Radiother. Oncol. **91** 3 (2009) 405–414.
[140] TSURUTA,Y., et al., Dosimetric comparison of Acuros XB, AAA, and XVMC in stereotactic body radiotherapy for lung cancer, Med. Phys. **41** 8 (2014) 081715.
[141] FRAGOSO, M., et al., Dosimetric verification and clinical evaluation of a new commercially available Monte Carlo-based dose algorithm for application in stereotactic body radiation therapy (SBRT) treatment planning, Phys. Med. Biol. **55** 16 (2010) 4445–4464.
[142] KUNZLER, T., FOTINA, I., STOCK, M., GEORG, D., Experimental verification of a commercial Monte Carlo-based dose calculation module for high-energy photon beams, Phys. Med. Biol. **54** 24 (2009) 7363–7377.
[143] FOTINA, I., et al., Advanced kernel methods vs. Monte Carlo-based dose calculation for high energy photon beams, Radiother. Oncol. **93** 3 (2009) 645–653.
[144] FOGLIATA, A., et al., On the dosimetric behaviour of photon dose calculation algorithms in the presence of simple geometric heterogeneities: comparison with Monte Carlo calculations, Phys. Med. Biol. **52** 5 (2007) 1363–1385.
[145] RICHTER, C., PAWELKE, J., KARSCH, L., WOITHE, J., Energy dependence of EBT-1 radiochromic film response for photon (10 kVp-15 MVp) and electron beams (6-18 MeV) readout by a flatbed scanner, Med. Phys. **36** 12 (2009) 5506–5514.
[146] AZANGWE, G., et al., Detector to detector corrections: a comprehensive experimental study of detector specific correction factors for beam output measurements for small radiotherapy beams, Med. Phys. **41** 7 (2014) 072103.
[147] FOLLOWILL, D.S., et al., The Radiological Physics Center's standard dataset for small field size output factors, J. Appl. Clin. Med. Phys. **13** 5 (2012) 282–289.
[148] FOLLOWILL, D. S., et al., Erratum: "The Radiological Physics Center's standard dataset for small field size output factors", J. Appl. Clin. Med. Phys. **15** 2 (2014) 356–357.
[149] KERNS, J.R., et al., Technical Report: Reference photon dosimetry data for Varian accelerators based on IROC-Houston site visit data, Med. Phys. **43** 5 (2016) 2374–2386.
[150] KERNS, J.R., et al., Reference dosimetry data and modeling challenges for Elekta accelerators based on IROC-Houston site visit data, Med. Phys. **45** 5 (2018) 2337–2344.
[151] SUMING, L., HAO, W., ZHIJIAN, H., XIAN, X., YANQIU, D., Development of the measurement method for MLC small field output factor in intensity modulated radiation therapy (IMRT), Chin. J. Radiol. Med. Prot. **35** 10 (2015) 775–779.

[152] CHELMINSKI, K., BULSKI, W., A multi-centre analytical study of small field output factor calculations in radiotherapy, Phys. Imag. Radiat. Oncol. **6** Suppl. 1 (2018) 1–4.
[153] XIAOJUN, C., CHUANPENG, H., CHENZHI, J., SUMING, L., HAO, W., Methods of verification and measurement of MLC-defined small field output factors for eight medical accelerators in Henan province, Chin. J. Radiol. Med. Prot. **35** 10 (2015) 780–783.
[154] KRON, T., et al., Small field segments surrounded by large areas only shielded by a multileaf collimator: comparison of experiments and dose calculation, Med. Phys. **39** 12 (2012) 7480–7489.
[155] LAUB, W.U., WONG, T., The volume effect of detectors in the dosimetry of small fields used in IMRT, Med. Phys. **30** 3 (2003) 341–347.
[156] ASPRADAKIS, M.M., BYRNE, J.P., PALMANS, H., ROSSER, K., WARRINGTON, A.P., Institute of Physics and Engineering in Medicine (IPEM) report 103: Small Field MV Photon Dosimetry, IPEM, York (2010).
[157] INTERNATIONAL ATOMIC ENERGY AGENCY, Commissioning of Radiotherapy Treatment Planning Systems: Testing for Typical External Beam Treatment Techniques: Report of the Coordinated Research Project (CRP) on Development of Procedures for Quality Assurance of Dosimetry Calculations in Radiotherapy, IAEA-TECDOC-1583, IAEA, Vienna (2008).
[158] CHUI, C.S., SPIROU, S., LOSASSO, T., Testing of dynamic multileaf collimation, Med Phys **23** 5 (1996) 635–641.
[159] ALVES, L., GABRIEL, V., Film2Dose: an research intended tool to access the combined standard uncertainty on radiochromic film dosimetry using multi-channel optimization, [Poster Presentation], International Conference on Advances in Radiation Oncology #ICARO2 (2017).
[160] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Prescribing, Recording, and Reporting Photon-Beam Intensity-Modulated Radiation Therapy (IMRT), ICRU Report 83, ICRU, Bethesda, MD (2010).
[161] WEBER, D.C., TOMSEJ, M., MELIDIS, C., HURKMANS, C.W., QA makes a clinical trial stronger: evidence-based medicine in radiation therapy, Radiother. Oncol. **105** 1 (2012) 4–8.
[162] PAPANIKOLAOU, N., et al., Tissue Inhomogeneity Corrections for Megavoltage Photon Beams: Report by Task Group 65 of the Radiation Therapy Committee of the American Association of Physicists in Medicine, Medical Physics Publishing, Madison, WI (2004).
[163] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115, IAEA, Vienna (1996).
[164] HALVORSEN, P.H., et al., AAPM Task Group 103 report on peer review in clinical radiation oncology physics, J. Appl. Clin. Med. Phys. **6** 4 (2005) 50–64.
[165] STERN, R.L., et al., Verification of monitor unit calculations for non-IMRT clinical radiotherapy: report of AAPM Task Group 114, Med. Phys. **38** 1 (2011) 504–530.
[166] HULTQVIST, M., FERNANDEZ-VAREA, J.M., IZEWSKA, J., Monte Carlo simulation of correction factors for IAEA TLD holders, Phys. Med. Biol. **55** 6 (2010) N161–166.
[167] HOROWITZ, Y.S., Theory of thermoluminescence gamma dose response: The unified interaction model, Nucl. Instrum. Meth. B **184** 1–2 (2001) 68–84.
[168] McKEEVER, S.W.S., MOSCOVITCH, M., TOWNSEND, P.D., Thermoluminescence dosimetry materials: properties and uses, Nuclear Technology Publishing, Ashford, (1995).
[169] ARIB, M., YAICH, A., MESSADI, A., DARI, F., Optimum parameters of TLD100 powder used for radiotherapy beams calibration check, Med. Dosim. **31** 3 (2006) 184–189.
[170] BATES, D. M., WATTS, D. G., Nonlinear Regression Analysis and Its Applications, John Wiley & Sons, Inc., New York (1988).
[171] PRESS, W.H., FLANNERY, B.P., TEUKOLSKY, S.A., VETTERLING, W.T., Numerical Recipes in Fortran 77: The Art of Scientific Computing, 2nd edn, Cambridge University Press, New York (1992).
[172] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Evaluation of measurement data: Guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections), ISO, Geneva (2008).
[173] LICHTEN, W., Data and Error Analysis, Prentice Hall, Upper Saddle River, NJ (1999).
[174] HULQVIST, M., Analysis of the uncertainties in the IAEA/WHO TLD postal dose audit programme. MSc Thesis, Stockholm University 2007.
[175] NIROOMAND-RAD, A., et al., Radiochromic film dosimetry: recommendations of AAPM Radiation Therapy Committee Task Group 55. American Association of Physicists in Medicine, Med. Phys. **25** 11 (1998) 2093–2115.
[176] AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE, Task Group No. 235 — Radiochromic Film Dosimetry: An Update to TG-55, Med. Phys. **47** 12 (2020) C1, i-vii, 5969-6567.

[177] SCHOENFELD, A.A., WIEKER, S., HARDER, D., POPPE, B., The origin of the flatbed scanner artifacts in radiochromic film dosimetry-key experiments and theoretical descriptions, Phys. Med. Biol. **61** 21 (2016) 7704–7724.
[178] LEWIS, D., CHAN, M.F., Correcting lateral response artifacts from flatbed scanners for radiochromic film dosimetry, Med. Phys. **42** 1 (2015) 416–429.
[179] HUSSEIN, M., ROWSHANFARZAD, P., EBERT, M.A., NISBET, A., CLARK, C.H., A comparison of the gamma index analysis in various commercial IMRT/VMAT QA systems, Radiother. Oncol. **109** 3 (2013) 370–376.

LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
CAG	Clinical Advisory Group
CRP	coordinated research project
CT	computed tomography
CTDI	computed tomography dose index
DAC	dosimetry audit centre
DAN	dosimetry audit network
EAG	external audit group
EBT	external beam therapy
EQUAL	Quality Assurance Network for Radiotherapy
ESTRO	European Society for Radiation Oncology
IC	ionization chamber
IMRT	intensity modulated radiation therapy
IROC	Imaging and Radiation Oncology Core
IROC-H	IROC Houston QA Center
LC	local radiotherapy centre
MC	measuring centre
MLC	multileaf collimator
MPG	medical physics group
MU	monitor unit
OAR	organ at risk
OD	optical density
OSLD	optically stimulated luminescence dosimeter
PMMA	poly(methyl methacrylate)
PSDL	Primary Standards Dosimetry Laboratory
PTV	planning target volume
QA	quality assurance
QUATRO	Quality Assurance Team for Radiation Oncology
RDS	Radiation Dosimetry Service

RPLD	radiophotoluminescence (glass) dosimeter
RTTQA	Radiotherapy Trials QA Group
SAD	source to axis distance
SBRT	stereotactic body radiation therapy
SD	standard deviation
SRS	stereotactic radiosurgery
SSD	source to surface distance
SSDL	Secondary Standards Dosimetry Laboratory
TL	thermoluminescence
TLD	thermoluminescent dosimeter
TPS	treatment planning system
VMAT	volumetric arc therapy

ANNEX: SUPPLEMENTARY FILES

The on-line supplementary files for this publication, which can be found on the publication's individual web page at www.iaea.org/publications, include examples of the radiotherapy infrastructure questionnaire, dosimetry audit instruction sheets, data sheets and results reporting forms. They have been prepared for audit steps 1−9 to specify the irradiation conditions and to collect the information necessary for dosimeter evaluation and data analysis, as well as practical instructions for DANs (see the following list for more information). The IAEA is not responsible for the content of the Member State reports, and all questions must be directed to the individual authors or organizations.

Package 1: Radiotherapy infrastructure questionnaire

Package 2: Instructions, data sheets and results reporting forms for the step 1 audit

Package 3: Instructions, data sheets and results reporting forms for the step 2a audit

Package 4: Instructions, data sheets and results reporting forms for the step 2b audit

Package 5: Instructions, data sheets and results reporting forms for the step 3 audit

Package 6: Instructions, data sheets and results reporting forms for the step 4 audit

Package 7: Instructions, data sheets and results reporting forms for the step 5 audit

Package 8: Instructions, data sheets and results reporting forms for the step 6 audit

Package 9: Instructions, data sheets and results reporting forms for the step 7a audit

Package 10: Instructions, data sheets and results reporting forms for the step 7b audit

Package 11: Instructions, data sheets and results reporting forms for the step 8 audit

Package 12: Instructions, data sheets and results reporting forms for the step 9 audit

CONTRIBUTORS TO DRAFTING AND REVIEW

Adolfson, E.	Linköping University, Sweden
Alm Carlsson, G.	Linköping University, Sweden
Alonso Samper, J.L.	National Control Center for Medical Devices, Cuba
Alves, V.G.	Instituto Nacional de Cancer, Brazil
Arib, M.	Centre de recherche nucléaire, Algeria
Azangwe, G.	International Atomic Energy Agency
Babu, R.	Bhabha Atomic Research Centre, India
Bera, P.	International Atomic Energy Agency
Bokulic, T.	International Atomic Energy Agency
Bulski, W.	The Maria Skłodowska-Curie Memorial Cancer Center and Institute of Oncology, Poland
Campos de Araujo, A.M.	Instituto Nacional de Cancer, Brazil
Castellanos, M.E.	Instituto de Investigaciones en Geociencias, Mineria y Quimica, Colombia
Chelminski, K.	The Maria Skłodowska-Curie Memorial Cancer Center and Institute of Oncology, Poland
Dutreix, A.	Consultant, France
Ekendahl, D.	National Radiation Protection Institute, Czech Republic
Followill, D.	M.D. Anderson Cancer Center, United States of America
Georg, D.	Medizinische Universität Wien, Austria
Gwiazdowska, B.	The Maria Skłodowska-Curie Memorial Cancer Center and Institute of Oncology, Poland
Izewska, J.	International Atomic Energy Agency
Kannan, A.	Bhabha Atomic Research Centre, India
Kazantsev, P.	International Atomic Energy Agency
Koniarova, I.	National Radiation Protection Institute, Czech Republic
Kry, S.	M.D. Anderson Cancer Center, United States of America
Lechner, W.	Medizinische Universität Wien, Austria
Li, K.	National Institute of Radiation Protection and Nuclear Safety, China
Lingatong, N.	Secondary Standard Dosimetry Laboratory, Philippines
Luong, D.T.	Vietnam Atomic Energy Commission, Viet Nam

Mahant, A.K.	Bhabha Atomic Research Centre, India
Novotny, J.	National Radiation Protection Institute, Czech Republic
Panyam, V.	Bhabha Atomic Research Centre, India
Povall, J.	University of Leeds, United Kingdom
Salikin, S.	Malaysian Institute for Nuclear Technology Research, Malaysia
Saravi, M.	Comisión Nacional de Energía Atómica, Argentina
Sergieva, K.	University Hospital Queen Giovanna, Bulgaria
Srimanoroth, S.	Ministry of Public Health, Thailand
Stefanic, A.	Comisión Nacional de Energía Atómica, Argentina
Suoming, L.	National Institute of Radiation Protection and Nuclear Safety, China
Tatcher, M.	Israel Cancer Association, Israel
Tenhunen, T.	Helsinki University Central Hospital, Finland
Thwaites, D.	University of Sydney, Australia
Tomsej, M.	CHU Charleroi Hospital, Belgium
van der Merwe, D.	International Atomic Energy Agency
Viegas, C.	Instituto Nacional de Câncer, Brazil
Wesolowska, P.	International Atomic Energy Agency
Zackova, H.	National Radiation Protection Institute, Czech Republic

Research Coordination Meetings
Vienna, Austria: 6−10 October 1997, 4−8 December 2000,
30 September–4 October 2002, 4−8 October 2004, 13−18 November 2006,
8−12 June 2009, 5−9 December 2011,
16−18 December 2013, 28 September–2 October 2015

Consultants Meetings
Vienna, Austria: 5−8 December 1994,
18−22 June 2001, 20−24 October 2003, 12−16 December 2005,
30 July–3 August 2007, 1−5 September 2008, 26−30 July 2010,
10−14 September 2012, 17–21 December 2012,
5−9 May 2014, 3−7 October 2016, 11−15 December 2017

IAEA
International Atomic Energy Agency

No. 26

ORDERING LOCALLY

IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

NORTH AMERICA

Bernan / Rowman & Littlefield

15250 NBN Way, Blue Ridge Summit, PA 17214, USA
Telephone: +1 800 462 6420 • Fax: +1 800 338 4550

Email: orders@rowman.com • Web site: www.rowman.com/bernan

REST OF WORLD

Please contact your preferred local supplier, or our lead distributor:

Eurospan Group

Gray's Inn House
127 Clerkenwell Road
London EC1R 5DB
United Kingdom

Trade orders and enquiries:

Telephone: +44 (0)176 760 4972 • Fax: +44 (0)176 760 1640
Email: eurospan@turpin-distribution.com

Individual orders:

www.eurospanbookstore.com/iaea

For further information:

Telephone: +44 (0)207 240 0856 • Fax: +44 (0)207 379 0609
Email: info@eurospangroup.com • Web site: www.eurospangroup.com

Orders for both priced and unpriced publications may be addressed directly to:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 26007 22529
Email: sales.publications@iaea.org • Web site: www.iaea.org/publications

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA