INTERCOMPARISON PROCEDURES IN THE DOSIMETRY OF HIGH-ENERGY X-RAY AND ELECTRON BEAMS

REPORT OF AN ADVISORY GROUP MEETING
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
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REPORT AND RECOMMENDATIONS OF THE ADVISORY GROUP

1. Introduction

The aim of radiotherapy is to achieve the best tumour control with a minimum of radiation-induced complications in critical normal tissues. The implementation of this object depends upon various factors. The present report, however, concerns itself specifically with the improvement of dosimetry and its uniformity.

All present biological and clinical evidence indicates that at a critical absorbed dose level, a difference in absorbed dose of less than 10% produce differences in biological effects as far as tumour control and normal tissue reactions are concerned [1, 2].

A possible procedure for achieving the goal of improving dosimetry is to send an expert to the various radiotherapy centres and have an on-the-spot dose determination. Another way of achieving this would be to greatly enlarge educational programmes for the training of medical physicists and other persons responsible for radiation dosimetry in their own centres. A third procedure is to make use of a mailed dose meter for the determination of absorbed dose.

A postal dose intercomparison programme of absorbed dose for ^{60}Co γ-rays was initiated by the IAEA in 1966, and has continued, on a larger scale, since 1970 with WHO collaboration. Thermoluminescence dosimetry was used for this study. In 1976, an Advisory Group to the IAEA recommended to extend the same technique for dose intercomparison to the field of orthovoltage X-rays.

The present report deals with the extension of the postal absorbed dose intercomparison programme to high-energy photon and electron beams.

The need for accurate dosimetry in this field is well recognized and results from the proliferation of these machines. The increased use of high-energy photon and electron beams means that the early indication of an incorrect absorbed dose as shown by an acute skin reaction is eliminated. Moreover, the reduced skin reaction allows for higher tumour doses. In this situation the accuracy of the dosimetry is revealed only in late radiation effects with a latent period of at least several months. Therefore the absorbed dose given by high-energy photon and electron beams must be well established.

2. Objectives

The objectives of the planned postal dose intercomparison programme are similar to those formulated in a former IAEA report (TRS No. 182).

(a) To create a greater awareness of the need for correct dosimetry in radiation therapy.

(b) To compare and improve the accuracy of the clinical delivery of the radiation dose.

(c) To improve dosimetric consistency within and among radiation therapy centres.

(d) To identify some of the sources of error in the delivery of the target absorbed dose as well as methods by which these may be corrected.

3. Specific aims

The aim of the present programme is to extend the postal dose intercomparison programme initiated by the IAEA and the WHO to high-energy radiation emitted by betatrons, linear accelerators, and other similar equipment, i.e.:

- X-rays of maximum energy of 20to 50 MeV
- Electrons with nominal energy of 2 to 50 MeV

The dosimeters which, up to now, have been proposed and used for such postal intercomparisons are the $FeSO_4$ chemical dosimeter and the thermoluminescence dosimeter. Their respective advantages and disadvantages are discussed here, taking into account their general merits as well as practical considerations.

For this intercomparison the choice of the dosimetric method as well as of the technical procedures should be such as to provide a determination of absorbed dose with an uncertainty of less than $\pm$ 5%.

As for the other energy ranges already investigated, the planned intercomparison programme should help in the assessment of the reasons for significant discrepancies, if such discrepancies occur.

4. Methods

4.1. General

Two methods that could be used to meet the specific aims are thermoluminescence and ferrous sulphate dosimetry.

4.2. Thermoluminescence Dosimeters

4.2.1. Lithium Fluoride Powder

The ongoing IAEA/WHO postal dose intercomparison programme is based on LiF powder. The system and its characteristics have been described elsewhere [3,4]. The reproducibility of the dosimeters irradiated in a ^{60}Co beam, in particular, has been evaluated and is $\pm$ 1,5% at the 95% confidence level. This figure has been obtained by dividing the LiF powder, in each dosimeter into 5 equal parts and taking the average of these readings.

Preliminary experiments indicate the energy-dependence of the system for photons with a maximum energy of 4 to 25 MeV is less than 2% [5].

Data from the same experimental study indicate that the energy dependence of the system for high-energy electrons is greater than that for high-energy X-rays (i.e. 10% in the range from 4 to 20 MeV).

4.2.2. Pressed Lithium Fluoride Thermoluminescence Dosimeters (TLD "chips")

Pressed LiF TLD chips have been used without build-up in surveys of dose delivery during clinical radiographic procedures [6,7] and in sealed glass bulbs for an extensive one-time survey of ^{60}Co teletherapy dosimetry [8,9,10]. LiF TLD in the pressed form has the advantage over LiF TLD powder of faster reproducible readout in equipment lending itself readily to partial automation of dosimeter handling. A disadvantage is the need for either individual dosimeter calibration between successive mailings or for selection and calibration of dosimeters of comparable response to identical irradiation.

The relative standard deviation from the mean response of individual chips varies somewhat from dosimeter to dosimeter. On the average, at the 95% confidence interval for the mean response of an individual bare dosimeter chip irradiated 9 times at one given level and read in a hot-nitrogen reader it was about $\pm$ 1,0 percent; that for an individual sealed bulb in which the two enclosed chips are permanently in contact with an electrically heatable metal strip was about $\pm$ 0,6 percent. When the quantity of dosimeters handled is in the thousands, it becomes cumbersome to keep up with dosimeter identity. In this case, a batch calibration is preferable. If one selects a batch of dosimeters of which, on the average, the individual dosimeter readings vary by about $\pm$ 3 percent, one obtains a mean response from 9 identically irradiated dosimeters for which at the 95 percent confidence interval the standard deviation is about $\pm$ 1,5 percent.

4.3. Ferrous Sulphate Dosimeter (Fricke Dosimeter)

The ferrous sulphate dosimeter is extensively used by National Standardizing Laboratories for calibration and for intercomparison, both by postal services [11, 12, 13, 14]. Since 1965, the IAEA also has carried out postal intercomparisons based on this method [15].

The following advantages of the ferrous sulphate technique are particularly applicable here:

1) High precision (within ± 0,5% at the 95% confidence level) and accuracy (within ± 2% for ^{60}Co, better than within ± 5% for the radiation qualities under consideration).
2) Change in the energy response of less than 1% for the radiation qualities under consideration.
3) Approximate water equivalence.
4) Dose rate independent response over the dose rate range in clinical use [12, 13, 14].

However, acceptable precision can only be obtained if particular care is taken in the preparation, handling and evaluation of this dosimetric technique. Thus, from a practical point of view, certain disadvantages must be taken into account:

1) The method is relatively laborious and expensive.
2) Since the ferrous sulphate solution is acid and poisonous, postal regulations in many countries prohibit its conveyance by ordinary mail.
3) The reliability of the solution might decrease when the time between preparation and evaluation exceeds a few months.
4) Higher absorbed doses than those used in clinical application have to be delivered.
5) An energy dependent perturbation factor is introduced by the glass container.

4.4. Recommended Procedure

It is recommended that the established ^{60}Co postal dose intercomparison by LiF powder be extended to high-energy X-rays. A depth of 10 cm in water for the capsules is recommended for these irradiations. Corrections for measured light versus absorbed dose given to water for the quality under consideration must be made and may be based on the nominal energy.

It is recommended that the absorbed dose intercomparison for high-energy electrons also is by LiF powder. To meet the accuracy required, correction for the energy dependence has to be made. This correction can be made on the basis of nominal energy, supplemented by information derived from depth dose curves provided by the participant.

For electron beams of energy lower than 8 MeV, experimental difficulties in determining the dose accurately with LiF dosimeters will increase due to the disturbances of the fluence caused by the dosimeter and its holder. In addition, the accurate positioning of the dosimeter becomes crucial due to the characteristics of the depth dose curves at low energies. For these reasons, it is unlikely that the uncertainty of the dose evaluation of $\pm$ 5% can be achieved for energies <8 MeV. However, since electron beams of these energies are used clinically and since their dosimetry is difficult, an intercomparison would be valuable even with an uncertainty in the range of $\pm$ 10%.

For the planned IAEA/WHO postal dose intercomparison, the depth of irradiation for electron beams will be established after the completion of the experimental study mentioned in action 5.

4.5. Actions in Case of Intercomparison Discrepancies

All participants will be informed of their results and in particular of the deviation between the quoted absorbed dose and the dose determined by the IAEA. It is generally recognized that a deviation of up to $\pm$ 5% in dose is within the presently accepted requirements for effective radiotherapy.

For larger deviations, it is important for the participant to investigate the causes and to attempt to improve his dosimetry procedure.

For deviations above 10%, it is recommended that IAEA/WHO take the following measures:

1. Inform the participant immediately.
2. Advise the participant to participate in the next planned intercomparison.
3. Attempt to determine the probable reasons for the observed discrepancy from the analysis of the data sheet and provide this information to the participant, together with a copy of the guidelines compiled for this purpose (see Appendix 5).

For deviations greater than 15%, it is recommended that the following additional measures be taken by IAEA/WHO:

1. Send a letter immediately to the radiotherapist in charge and/or the phycisist who carried out the intercomparison, urging him to repeat the dosimetry and check all computations of absorbed dose. The contents of this letter should be considered strictly confidential, inasmuch as it may involve the treatment of patients.
2. If the preceding step confirms the previous results, recommend to to the participant to have his dosimeter calibrated immediately.

5. General Recommendations

While there is a necessity for dosimetric intercomparison for all energies and modalities used in radiation therapy there is an especial urgency to perform an intercomparison of dosimetry for high-energy X-ray and electron equipment. This necessity is brought about by the rapid proliferation of this type of equipment and the possibility of serious dosimetry errors due to the complexity of the medical accelerators and the dosimetric procedures. For high-energy X-rays the risk of accident due to overdoses is increased by the reduced early skin reactions. Thus the radiotherapist can inadvertently deliver high doses without producing visible severe reactions.

Therefore, this Advisory Group recommends :

1) Users of high-energy X-ray and electron machines should be encouraged to conduct radiation therapy only with the participation of a qualified medical physicist;
2) An international postal absorbed dose intercomparison programme of high-energy photons and electrons should be initiated by IAEA/WHO at the earliest possible date to be followed by similar SSDL programmes. The following studies should be included:
   a) A pilot study should be conducted for high-energy X-rays. A sufficient number of institutions in various countries and with different machines should be included.
   b) For high-energy electrons, the experimental study of precision and energy dependence of the LiF system should be continued by IAEA. Measurements with $FeSO_4$ should be included. It is recommended that one of the well-established centers already carrying out $FeSO_4$ dosimetry provide this service.
   c) In view of the importance of the IAEA/WHO intercomparison service, it is recommended that the IAEA take measures to make this service available to a wider international community, maintaining the present high-level of performance.

APPENDIX

INTERCOMPARISON OF ORTHOVOLTAGE THERAPY DOSIMETRY

In the report of recommendations of an Advisory Group Meeting, organized by the International Atomic Energy Agency and held in Vienna, 6 - 10 December 1976, a pilot study of the X-ray postal dose intercomparison technique for orthovoltage therapy was requested. The pilot study was conducted in the summer of 1977 and the results were reported [16].

The conclusions of the pilot study were, in summary:

a) The external filter technique for determining HVL is practical over the quality range of interest and is necessary for the purpose of correcting the TLD signal for the energy dependence of LiF.

b) The LiF TLD technique provides sufficient precision and reliability and meets the requirements of the Advisory Group (1976) that "the accuracy of the dose determination should be better than $\pm$ 10% and preferably $\pm$ 5%..

The 1979 Advisory Group confirms these conclusions and recommends that the IAEA/WHO and the SSDL's conduct intercomparisons in the orthovoltage energy range using this technique, adhering to the conclusions of the pilot study and the recommendations of the 1976 Advisory Group.

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APPENDIX I

IAEA/WHO POSTAL DOSE INTERCOMPARISON (TLD) FOR HIGH ENERGY X-RAY THERAPY

INSTRUCTION SHEET

ATTENTION: to obtain appropriate results IT IS ESSENTIAL TO EXPOSE AND RETURN THESE DOSIMETERS IN NO CASE LATER THAN

.....

to the address given in the covering letter. Exceeding the time limit entails uncertainties in the results. Such dosimeters may even have to be disregarded.

If you are unable to carry out the irradiation before the date indicated above, RETURN the set before the deadline, marking it "UNEXPOSED".

WARNING: Capsules must never be exposed to heat (e.g. sunshine), nor stored in a place where accidental exposure to ionizing radiation cannot be excluded.

TECHNICAL INSTRUCTIONS:

Please read all the following instructions carefully before you start irradiating the capsules. Also complete the DATA SHEET carefully; only then is an evaluation of the results and appropriate advice possible.

A. Preparation of the holder and water phantom

1. The parts of the holder are shown in Fig. i. There is a long lucite tube with a hole in it across its long axis, attached to a (red) disc at one end. The disc has three holes. Also in Fig. i are shown three (red) sticks. The sticks can be fitted into the holes if the disc and the holder is then ready for use. (Looks as shown in Fig. ii.).

(Caution: the parts of the holder are to be handled carefully as otherwise deformation will result).

2. Place a waterproof container made of any material available and having a minimum length, width and height of 30 cm each, in a vertical X-ray beam. Align the center of the container with the central axis of the beam.

3. Place the holder into the container in such a way that the plastic tube is aligned with the central axis of the beam.

4. Fill the container with water exactly to the level of the top end of the holder.
Check that the plastic tube is completely filled with water and, in the case the TLD capsule is to be inserted while the holder is in the water, check also that its alignment has not changed.

B. Exposing the LiF capsules

The insertion of TLD capsules may be performed before the holder is placed into the container after the full alignment of the holder with the X-ray beam. The decision is left to the user.

1. Use a 10 x 10 cm field at your normal source to surface distance (SSD) (or source to centre-of-capsule distance if you normally use an isocentric set-up).

2. Insert one of the three LiF capsules to be exposed by you into the hole at the upper part of the tube of the holder. Insert first the bottom end of the capsule (as shown in Fig. iv) to avoid opening by accident. Place the capsule so that it shows extends equally on both sides of the tube (Fig. v). Now the capsule is at 10 cm depth in water and ready for exposure (Fig. iii). Recheck alignment, water level and distance.

3. Calculate the irradiation time according to the method used by you in your daily practice ("Guidelines for calculating absorbed dose ...",). Under these conditions irradiate one of the three LiF capsules to give an absorbed dose of 2 Gy (200 rad).

4. Remove the capsule from the holder by pushing against the bottom end of the capsule (Fig. vi).

5. Repeat procedure from 2 to 4 at the same machine with the same arrangement for each of the other two capsules, to be exposed for the same time.

6. The capsule with white stopper is for the purpose of checking environmental influences on the capsules during transport and storage and must not be irradiated; it should, however, be stored together with the others.

7. Throughout all procedures, handle the capsules very carefully to prevent opening and loss of powder.

C. Completion of the Data Sheet

1. Completion of the data sheet is essential for the evaluation of dosimeter readings; dosimeters without or with incomplete data sheets will not be evaluated. Give more information on an additional sheet, if you so wish.

2. Indicate irrelevant questions by "NA" = Not applicable.

3. In the data sheet use has been made of the new SI units. The old units are given in parenthes. If participants already employ them the data may be given in these units.

THANK YOU FOR HAVING READ AND FOLLOWED THESE INSTRUCTIONS

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APPENDIX II

IAEA/WHO POSTAL DOSE INTERCOMPARISON (TLD) FOR HIGH-ENERGY X-RAY THERAPY

DATA SHEET

(Please use BLOCK LETTERS or typewriter, particularly for names and addresses)

Name of institution .....

Address of institution .....

.....

Form completed by ....
(name) (position) (date)

Signature .....

Previous participation in the IAEA/WHO Cobalt-60 TLD intercomparison

No [ ] Yes [ ] date.....

or in the IAEA/WHO orthovoltage X-ray TLD intercomparison

No [ ] Yes [ ] date.....

or in the IAEA/WHO high-energy X-ray TLD intercomparison

No [ ] Yes [ ] date.....

It is of great importance for the evaluation that all information requested in the data sheet is filled in.

The data sheet cannot cover all possible measurement procedures. If a participant uses a procedure not covered by the data sheet, he is requested to give full details of his method on page 4.

A. Specification of the accelerator	
1. Type and model of accelerator	.....
2. Date of installation	.....
3. Nominal energy used for the irradiation of the IAEA dosemeters	.....

Details of Beam dosimetry	
1. Specification of dosemeter	
a) Type of dosemeter (ionization chamber)	.....
b) Serial number on the dosemeter	.....
c) Date of calibration	.....
d) Calibrating laboratory	.....
e) Calibration factor for Co-60	.....
f) At which temperature and pressure is the calibration factor valid	.....°C .....mmHg
g) Check source reference reading at time of calibration	.....
h) Radionuclide in check source	.....
2. Actual conditions at the time of the calibration of the beam.	
a) Type of monitor chamber in the accelerator	.....
b) Are pressure and temperatur corrections applied to the monitor reading	.....
c) Check source reading	.....
d) Check source reading corrected for decay	.....
e) Dosemeter reading	.....
f) Temperature in phantom during calibration (°C)	.....
g) Air pressure in the phantom during calibration (mmHg)	.....
h) Correction factor for temperature and air pressure	.....
i) Or correction factor derived from check source reading	.....
j) Correction factor for recombination in the dosemeter.	.....
k) Factor(s) used for converting dosemeter reading to absorbed dose to water	.....
l) Accelerator dose monitor setting	.....
m) Medium for measurement	.....

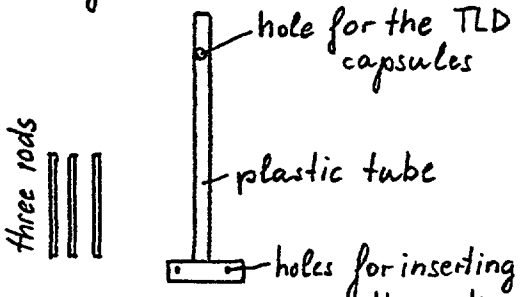
B. Beam dosimetry	
1. Date for calibration of the beam	.....
2. Source to detector distance (cm)	.....
3. Source to surface of the medium distance (cm)	.....
4. Field size at the surface of the medium or at the detector position (cm x cm)	.....
5. Beam calibration factor for the accelerator;	
a) absorbed dose per monitor unit (Gy/mon)	.....
b) at the depth in phantom of (cm)	.....
C. LiF-capsule irradiation	
Give values for only those factors that are used by you for calculation below. Write NA against whichever is not applicable. In your computation of absorbed dose to water, do not correct for the perturbation introduced by the LiF-capsule.	
1. Date of irradiation	.....
2. Source to water surface distance (SSD)(cm)	.....
3. Field size at the water surface or at the position of LiF capsule (cm x cm)	.....
4. Dose monitor setting	.....
5. Absorbed dose delivered to water at the irradiation of LiF capsules (Gy)	.....
In case your calibration depth is not identical with the depth at which the LiF capsule is irradiated (10 cm) please give the following additional information.	
6. Depth of calibration (cm)	.....
7. Percentage depth dose at calibration depth	.....
8. Percentage depth dose at a depth of 10 cm	.....

D. Please give in detail how you arrived at the figure given in B.5. (in case this is not clearly enough described by the data requested).

E. Full details of measurement procedures if not covered by this data sheet (see page 1).

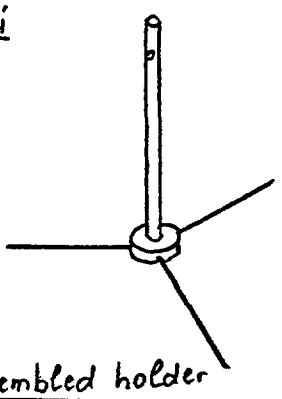
F. If you have suggestions to improve this intercomparison, please give details.

Fig. i



Holder for inserting the sticks

Fig. ii



Assembled holder

Fig. iiia

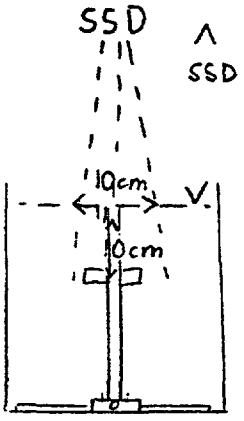


Fig. iiib

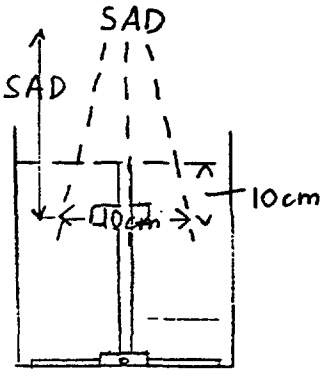


Fig. iv

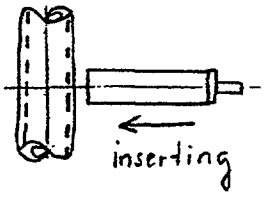


Fig. v

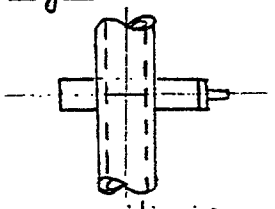
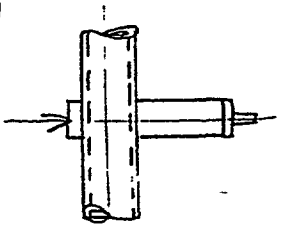


Fig. vi



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THE IAEA/WHO THERMOLUMINESCENT DOSIMETRY INTERCOMPARISON USED FOR THE IMPROVEMENT OF CLINICAL DOSIMETRY

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Introduction

A number of papers have already presented and analysed the IAEA/WHO TLD postal dose intercomparison for Co-60 teletherapy. Most of these have been devoted to the methodology or the results obtained without considering the use of these results to improve clinical dosimetry in centres where this has been shown necessary from the TLD results.

The present paper is based on the experience of the author in one of the Regional Offices of WHO where an attempt to use the TLD results to improve clinical dosimetry was made during the last five years.

Results of the TLD intercomparison in the Eastern Mediterranean Region of WHO

The results discussed here were obtained from 23 radiotherapy departments located in universities or specialized hospitals in 12 countries of the Eastern Mediterranean Region. All the given data represent dose and not dose rate and were obtained during 1971-1978 (TLD batches II-XXII). The results are presented in Table I by country and radiotherapy department.

Of the 104 measurements undertaken in the 23 departments 53.9% did not exceed ±5.0% deviation from the given dose, which is considered an acceptable limit for clinical dosimetry. The remaining 46.1% of measurements exceeded ±5.1% and therefore fall into the category of unacceptable precision for clinical dosimetry. Of this latter group 25.9% exceeded ±10.1% and of this 2.9% exceeded ±20.1% deviation, as can be seen from the last line in Table I.

An observation was also made concerning the ratio of positive to negative deviations; positive deviations meaning doses given which exceeded the given value and negative deviations those administered of less than the given value. All deviations in the range of ±5.0 - ±10.0% are equally distributed in the positive and negative areas, the ratio of positive to negative being just a little over the unity. Of deviations greater than ±10.0% a larger number are found to be negative, the negative/positive ratio being 1.7.

TLD results trends

Data from 16 radiotherapy departments have been set out to show their chronological evolution so that it may be seen whether the TLD intercomparison had an influence on the precision of the clinical dosimetry. The departments have been split into three categories according to their TLD results: 1) radiotherapy departments with good results (graph 1); 2) radiotherapy departments with acceptable results (graph 2); 3) radiotherapy departments with poor results (graph 3). The first and second graphs clearly show a tendency towards an improvement of the clinical dosimetry over the period covered and this can be attributed to the TLD intercomparison helping the medical physicists to check more carefully all the parameters involved in the measurement of the output of their Co-60 machines. Graph No. 3, on the contrary, shows that the TLD intercomparison had no significant influence on the procedures for measuring the Co-60 machine output in these seven radiotherapy departments. Only one department (Am) has subsequently produced deviations which are positive and do not differ greatly from one measurement to another. A second department

(Bg) has two erratic values (one of +6.5 and another of -21.0%) and five correct values. A third department (Tr) has two values which are -20.0% and -15.0% and one which is correct.

The deviations encountered in some other departments (Al, La, Ka) deviate for a certain period in the minus direction then suddenly after 1976-77 change to the opposite direction, only to alter again later on with the exception of Al, which remains with quite high positive deviations. This inconsistency of values obtained clearly shows inaccurate clinical dosimetry procedures and should be followed by an enquiry to the institutes concerned in order to detect the sources of errors. IAEA and WHO should concentrate their attention on those radiotherapy departments with results shown in Graph 3.

Discussion of the results and counter measure

In order to find an explanation for the deviations encountered a mission by a physicist with a calibrated secondary standard dosimeter was organized early in 1978 to the departments shown in Graph 3, with the exception of one. The findings of this investigation were that:

- the clinical dosimeters used by three of the departments were not working properly causing inconsistent data to be obtained;

- the remainder of the departments had one or more dosimeters in perfect working order but the procedure for measurement of the machine output was inadequate or the correction factors (pressure, temperature) were wrongly applied due to lack of reliable instruments for such measurements and/or inadequate training of the local medical physicists

As a result of this investigation a decision was taken to purchase three new clinical dosimeters for those departments where faulty dosimeters were being used and to organize a refresher course on clinical dosimetry for medical physicists from all departments with inconsistent results.

The experience presented here shows how the IAEA/WHO postal TLD intercomparison can be used to identify places where clinical dosimetry is of a low standard and to determine appropriate counter measures. In order to make further improvements it is suggested that the IAEA/WHO Network of Secondary Standard Dosimetry Laboratories should be actively involved in the assessment and follow-up of TLD results and in undertaking appropriate action to raise the level of clinical dosimetry.

Another essential factor to be considered is reducing the rather lengthy delay between receipt of the TLD dosimeters in Vienna and sending out the results to the various radiotherapy departments throughout the world. If this can be achieved a more direct impact on clinical dosimetry can be expected.

A final comment concerns the sending and return of the dosimeters and the need for improvement in this respect. The number of non-returned dosimeters remains high, some being lost in mailing either prior to or post irradiation, and others not being irradiated because of equipment being out of order.

A gradual improvement in the number of dosimeters being returned has taken place and better contact maintained with the various radiotherapy departments. Letters were sent to all departments to ascertain their willingness to participate in a given batch and dosimeters sent only to those which replied positively. Reminders were sent to all departments which did not return the dosimeters by the fixed deadline and this has caused the number which have not been returned to decrease substantially.

Mailing the dosimeters represents another constraint as postal and custom authorities sometimes use x-rays to check the content of packages or fear that packages might contain explosives. In the Eastern Mediterranean Region the existence of diplomatic pouches to most of the participating countries was of great help in forwarding and recovering the dosimeters.

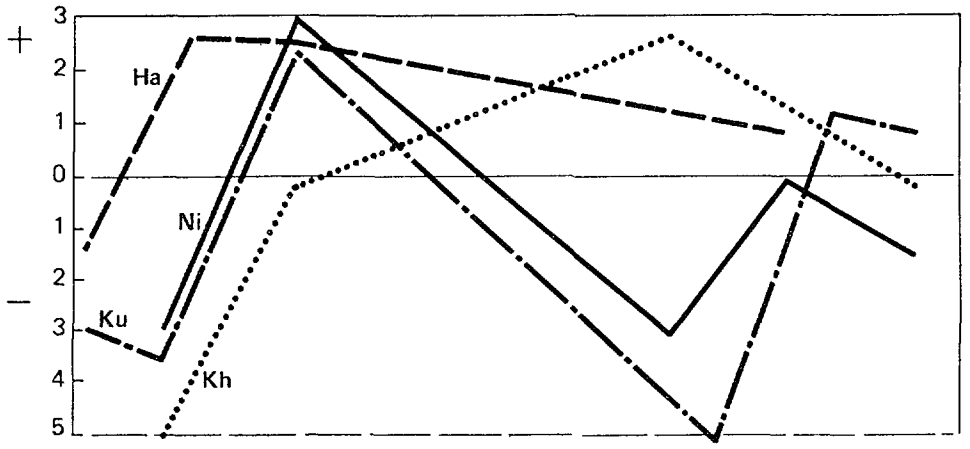
Table I

TLD Results expressed in Percentage Deviation from the Given Dose for 23 Radiotherapy Departments in 12 Eastern Mediterranean Countries

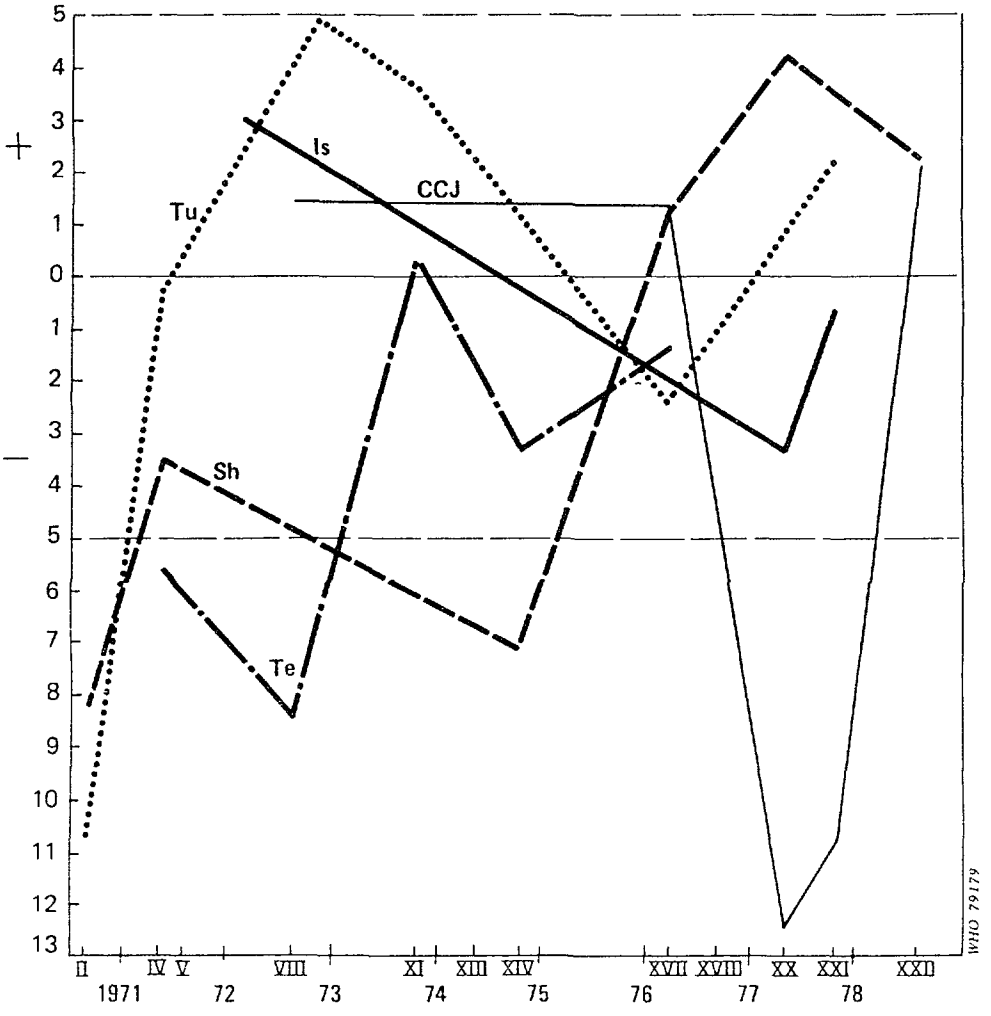
Country	RT Dept.	Total No.of Measurements 1971-1978	No. of measurements with a % deviation			
			±0 to ±5.0	±5.1 to ±10.0	±10.1 to ±20.0	over ±20.1
1	Ni	5	5	0	0	0
2	Al	6	0	3	2	1
	Cu	4	1	0	3	0
	Ccl	6	4	0	2	0
	Cm	3	0	1	2	0
3	A	2	2	0	0	0
	Is	3	3	0	0	0
	Sw	6	4	2	0	0
	Tcl	5	3	2	0	0
	TMH	2	1	0	1	0
4	Bg	7	5	1	0	1
5	Ha	4	4	0	0	0
6	Am	5	0	2	3	0
7	SH	6	5	1	0	0
8	TH	5	2	1	2	0
9	Ka	7	2	1	3	1
	La	6	2	0	4	0
	H	4	1	3	0	0
	M	2	0	2	0	0
	P	4	1	1	2	0
10	Ku	4	4	0	0	0
11	D	2	2	0	0	0
12	Tu	6	5	1	0	0
TOTAL:	23	104	56	21	24	3
%	-	100.0	53.9	20.2	23.0	2.9

TLD INTERCOMPARISON IN EMRO

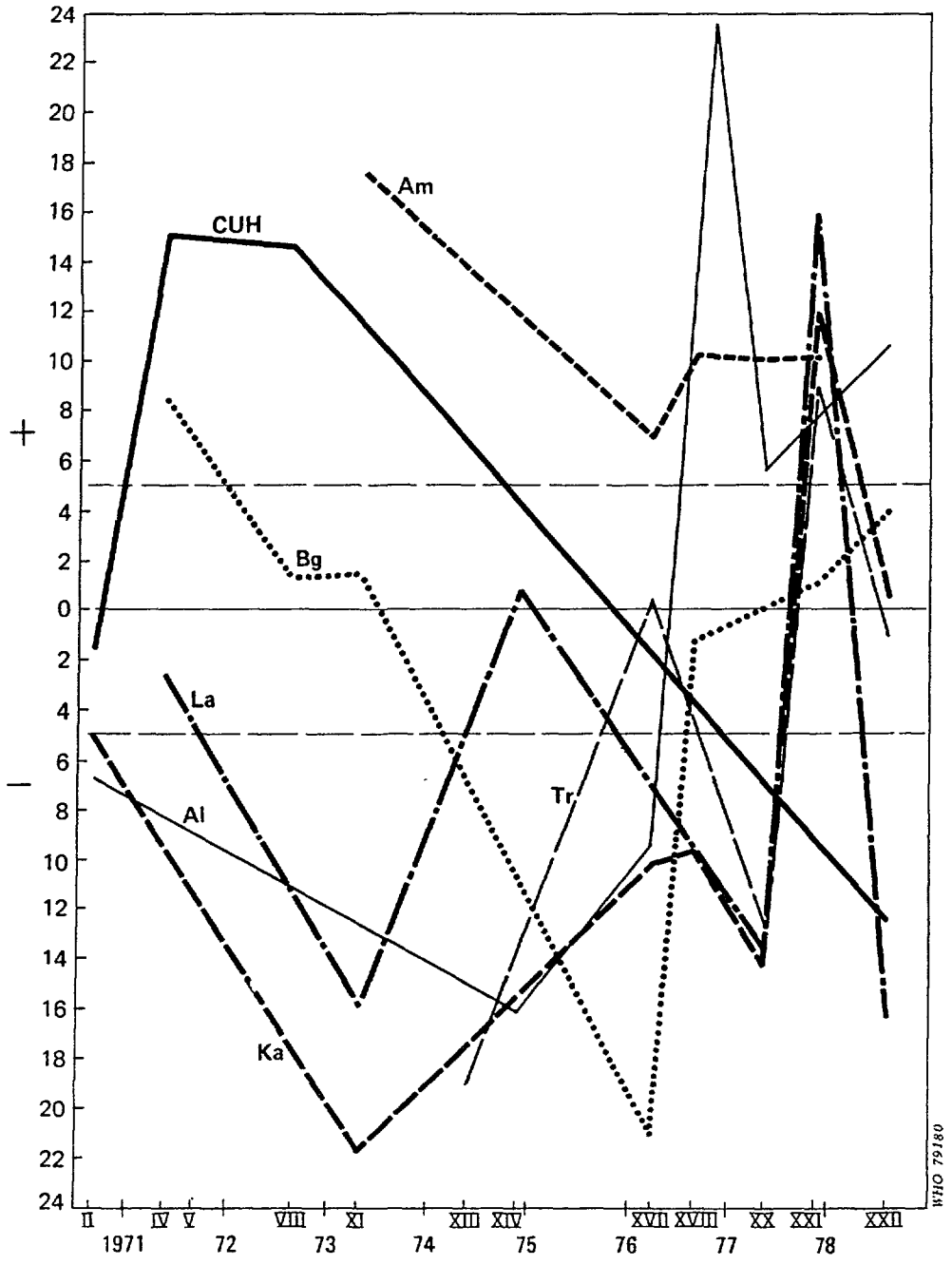
1 – RADIOTHERAPY DEPT WITH GOOD RESULTS



2 – RADIOTHERAPY DEPT. WITH ACCEPTABLE RESULTS



3 – RADIOTHERAPY DEPT WITH POOR RESULTS



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A SURVEY OF CLINICALLY APPLIED DOSIMETRY

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1. Introduction

Biological evidence has been obtained at the M.D. Anderson Hospital, Houston, Texas[1], according to which a difference of ±7% in applied dose in the therapeutic range already results in increased tumour recurrence in the case of underdosage and in aggravated side effects and damage in the case of overdosage. Unavoidable uncertainties in tumour localization and definition of the tumour volume in clinical routine work occupy practically fully this therapeutic range and the accuracy of the physical aspects of clinical dosimetry should therefore be much better than ±7%. The absolute accuracy of the realization of radiation units in Primary Standard Laboratories, e.g. NBS, NPL, PTB, is quoted in calibration certificates for clinical dosimeters to be about ±2 to 3%. Experience in the IAEA/WHO Network of Secondary Standard Dosimetry Laboratories (SSDLs) by intercomparing the calibration of a reference instrument in 17 laboratories has, however, demonstrated that the calibration of secondary standard dosimeters and the transfer of the unit of radiation to a "field instrument" agree on a worldwide scale to much better than ±2% if appropriately performed.

One major component of WHO's programme for improving, promoting and strengthening radiotherapy as an essential part of cancer control is therefore clinical radiation dosimetry. Three approaches are used:

(a) promotion of the training and education of medical physicists and their appointment in radiotherapy institutions as partners - not just auxiliaries - of the radiotherapist;

(b) establishing in all WHO Regions WHO Collaborating Centres for Secondary Standard Dosimetry (SSDLs) in order to facilitate for the user of radiation, the radiotherapy institute, access to calibrating facilities where the clinical dosimeters can be calibrated and regularly recalibrated.

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[1] Shukovsky, L.J.: Dose, time, volume relationships in squamous cell carcinoma of the supraglottic larynx; Am. J. Roentgenol. 108 (1970): 27-29.

This is necessary as individual dosimeters vary in sensitivity and energy response, etc., and their characteristics may even change with time. Accurate calibration of a dosimeter is, therefore, the first prerequisite for an accurate measurement of dose. Furthermore, an SSDL should build up regional and local expertise in the field of dosimetry, act as regional or national advisor to the user (radiotherapy institutes, but also radiation protection services and e.g. industrial users of radiation), and undertake educational and training activities in radiation physics and dosimetry. The target of this programme is the availability of at least one appropriately qualified SSDL in each major country in which the use of radiation and radionuclides is not just negligible and easy access to an SSDL in a neighbouring country for the user of radiation in a country without its own national SSDL. To meet that target, in close collaboration with and on the initiative of the International Atomic Energy Agency, the joint IAEA/WHO Network of SSDLs was established in 1976 and included (at September 1978) already 39 regular members, and 11 affiliated members (National Primary Standard Institutes, e.g. the National Bureau of Standards, NBS, Washington).

(c) Performing dose intercomparisons and surveys for radiotherapy institutes which allow the following to be checked:

(i) the validity of calibration of the clinical dosimeters used;

(ii) the accuracy of the irradiation equipment including its shutter mechanism and timing procedure;

(iii) the ability of the institute's staff to accurately set-up patients (checked by measurements on simple phantoms);

(iv) the professional capacity of staff to reliably make the dose calculations necessary for applying radiotherapy - such surveys furthermore allow:

(v) advice to be given to the individual institute in case of poor results on how to improve the quality of work and avoid mistakes;

(vi) decide whether sending a consultant to the institute to check locally the procedures applied and provide local training is necessary to improve the situation; or,

(vii) conclude that due to the frequency of events in a geographical region it is desirable to establish local or regional training activities in order to improve generally the level of professional competence in the relevant country or region.

In the long-term planning it is expected that finally each national SSDL, WHO Collaborating Centre or Member of the IAEA/WHO Network of SSDLs, performs such intercomparisons and surveys independently of each other in their geographical area of competence. International coordination by IAEA and WHO or the Network as such will then be limited to harmonising the methodology applied by the various SSDLs to make their results internationally comparable and to check whether systematic deviations occur.

Some SSDLs have already started to implement their own programmes for "postal dose intercomparisons" and are participating in an international programme, run by the IAEA, for comparing such programmes. The majority of countries in this world are, however, not yet covered by such national or regional programmes and this is the reason that IAEA and WHO still continue the "IAEA/WHO Postal Dose Intercomparison Programme". An evaluation of its results are presented in this paper.

2. The IAEA/WHO Postal Dose Intercomparison Programme

Apart from sending an expert with his own dosimetric equipment to a radiotherapy institution (RTI) for checking all procedures applied, there is only one possibility for intercomparing and surveying clinical dosimetry: this is sending (by mail or through other channels of communication) a dosimeter to the RTI, with the request that it be irradiated under prescribed conditions with a prescribed absorbed dose, and measuring the

absorbed dose received by the dosimeter after it has been returned. Unfortunately, the classical dosimetric method of measuring the number of ionizations produced by radiation in a defined volume, is not appropriate for that purpose. Other effects of radiation on matter need to be used. Considering the existing possibilities therefore IAEA in 1969 decided to investigate the use of the "Thermo-luminescent-dosimetry (TLD)" -principle for "postal dose intercomparisons". Details of this principle are described in many publications and therefore are not repeated here.

In 1970 WHO joined IAEA in the implementation of the project and the IAEA/WHO Postal Dose Intercomparison Programme started. In this programme IAEA was responsible for preparing the TLD sets of dosimeters and measuring the radiation dose received by the sets returned, WHO took care of the distribution and recollection of the dosimeters throughout the world, and acted together with IAEA on the evaluation of results, and initiating corrective measures where necessary.

In the following the results of the IAEA/WHO Postal Dose Intercomparison Programme are described and critically evaluated.

2.1 Methodology

Lithium-fluoride powder in plastic capsules - representing a thermoluminescent dosimeter (TLD) - is sent to participating institutions. The institutes are requested to irradiate these capsules under prescribed conditions with a prescribed radiation dose and return them through WHO channels to IAEA, where the radiation dose received by the capsules is measured. One "set" of dosimeters consists of 6-10 capsules of different kinds intended to evaluate the dose, doserate, additional dose received, or "fading" during transport, and consistency of results. The institutes also fill in a "data sheet", in which they describe how they calculated and arrived at the dose given to the capsules. The difference between the measured and quoted dose given in percent of the quoted indicates the accuracy of dosimetry in the relevant institute, whereby a negative deviation means that the dose really administered was smaller than intended (quoted) and vice versa. Accordingly, completed "data sheets" frequently enable the source of errors to be located. In other cases comprehensive correspondence, repetition of the measurement, or even sending an expert in dosimetry, solves the problem and improves the accuracy of radiotherapy in the relevant institute.

2.2 Results 1969-1978

In Document RAD 40/76 an evaluation of results up until 1976 was provided. The present evaluation, covering the period from 1969 to 1978 is, however, not just an extension from 1976 to 1978, but a revaluation of all data available by September 1978. Two to three batches of 40 to 80 sets of dosimeters were distributed and recollected annually. Details of the batches and their distribution to the six WHO regions are shown in Table 1. A total of 1011 sets of dosimeters have been distributed over 10 years and 85% of them recollected and evaluated. It needs to be mentioned that only a few of the unreturned, unirradiated or unevaluable dosimeters (all included in the tables as "not returned") were "dropouts" due to conditions out of control of the user, e.g. failure of mailing services, etc. Unfortunately the majority reflects the carelessness of the participating institute and lack of interest in improving the quality of its own work. Considering that material costs and the work of international staff involved amount to approximately US$ 50 per set of dosimeters, the waste of 15% of the dosimeters distributed is a waste of around US$ 8 000, leading to considerations of whether it is justifiable to perform such intercomparisons free of charge for the participating institutions, particularly as they represent direct assistance to countries rather than an investigation for the purpose of IAEA and WHO. Charging for participation in the programme would, however, have the adverse effect that many RTI interested in improving their quality of dosimetry are prevented from participating for administrative and budgetary reasons.

A similar observation was also made by WHO in distributing free of charge personnel monitoring dosimeters (film badges), which were fully financed by extra-budgetary contributions (provision to WHO free of charge by the Service Central de Protection contre les Ravonnements ionisants under Professor P. Pellerin and the Personnel Monitoring Service of the Gesellschaft für Strahlenschutz, Neuherberg, under Professor Wachsmann). Here again, the return rate is much lower than when participants are charged. The misuse and waste of services provided free of charge is a serious problem which needs further consideration.

In Table 2 data for 1969 to 1978 are split into WHO Regions, Africa has not yet participated in the programme (apart from pilot studies in which in 1969 South Africa and Southern Rhodesia were involved). RT has developed on this continent during the last few years only but this momentum will increase in the future. All other WHO regions participated nearly equally with around 1/5 each of the distributed dosimeter sets. Seventy countries, representing more than half of the WHO Member States participated, and altogether 416 RTI throughout the world were checked. 50% of them participated once only; 10% more than 5 times. The relatively high rate of 32-33% of institutes participating more than 5 times in the Eastern Mediterranean (EM) and South-East Asia (SEA) demonstrates the specific interest of some RTIs and particularly of the Regional Advisers in the WHO Regional Offices to get the situation under control. Considerable differences exist between regions in the percentage of "not returned etc." sets. This rate of "waste" is below 10% for the European Region and as high as 18 and 21% for the South-East Asia and Western Pacific Regions respectively.

In Table 3 the "not returned etc." sets of dosimeters are listed in relation to the frequency of participation of an RTI in the programme. It is interesting to note that 38% of all institutes which participated once or several times did not return the dosimeters at least once and 7.5% of all institutes did not return them two or more times. It is unfortunately obvious that such failures are not normally the fault of the mailing system in a country and failure to return a dosimeter should therefore be judged as a bad and unreliable result.

In the following, however, only results of returned and measurable sets of dosimeters are analysed. Table 4 provides the summary of data split according to WHO Regions and into periods of time, I including batches I to XI, and II including batches XII to XXIII respectively. The periods cover the years 1969-1973 and 1974-1978 respectively. The sum for both periods is also quoted as well as the world total. Finally, the results in a number of single countries are given whereby the relevant WHO Region is mentioned but the country's name codified. "Results" of the intercomparison are expressed as % deviation of the dose measured from the TLD by IAEA (M.M.) and the dose quoted by the relevant RTI as having been administered (0) to the capsules according to the formula.

$$\text{Deviation } \% = \frac{M.M. - 0}{0} \times 100$$

For the evaluation 7 classes of deviations are defined:

A = $\pm$2% B = $\pm$2.1 to 5% C = $\pm$5.1 to 10% D = $\pm$10.1 to 20%

E = $\pm$20.1 to 50% F = $\pm$50.1 to 100% and G = above $\pm$100%

In Table 4 the cumulative percentage of the number of results in the relevant class are quoted. 100% is the total number of dosimeter sets returned and evaluated for the relevant line. The third column therefore gives the percentage of results within $\pm$2%, the fifth column those within $\pm$10% (= the sum of class A + B + C). The sixth column includes the sum of D and all higher classes; in other words, all results above $\pm$10% and so on. The quality of results in the various classes can be defined as: A = excellent and a deviation of this size is not significant as it is within the maximum achievable accuracy of the TLD method under the given conditions. B = good and some values in this class near to 2% may even result from exceptionally greater random errors of the TLD method; if nearer to 5% they should, however, lead to a check being made of the irradiation and calculation procedures and the deletion of small errors, when detected. Class C = not good although not too serious and should lead to a careful check being made of all procedures applied, including perhaps a recalibration of the dosimeter if this result in the same direction (either plus or minus) is repeatedly obtained. The error in class D is totally unacceptable for effective radiotherapy and immediate steps need to be taken to locate and correct the error and improve the quality and accuracy of work. Class E and higher mean a total disaster if patients are treated with that accuracy. Serious consequences will result and immediate expert advice from outside the RTI, perhaps from a nearby SSDL, should be requested to locally check the procedures applied and give on-the-spot training.

In the last columns the number of countries included in the relevant line, the number of participating RTIs and the number of dosimeter sets distributed, are given. The final column gives the dosimeter sets which have not been returned, not irradiated or cannot be evaluated for various reasons in % of the number of sets distributed.

Although the table is self-explanatory a few points might, however, be extracted: the results vary considerably between the various regions. Africa (AF) should not be considered in this context as only a few selected RTI participated in the first pilot batches, in order to check the suitability of the intercomparison method. Good results within ±5% deviation over the whole period 1969-1978 were observed for a little over 50% of the measurements in Latin America (Latin-AM), Eastern Mediterranean (EM) and South-East Asia (SEA), whereas Europe (EU) and Western Pacific (WP) regions show more than 60 to 70% good results, compared with 59% for the world total. 28 and 29% of the results were not acceptable at all (more than ±10% deviation) in Latin-AM and EM respectively, compared with 10% for EU and 20% for the world total. 2% of the results for Latin-AM were out by more than ±50% during the first period and 0.5% for the world total in both periods.

A review of the data split according to single batches was made to check whether the situation had improved during the 10 years the programme has been running. This was not demonstrated as the proportion of each batch sent to the different regions varied considerably and the programme increasingly concentrated on regions and countries most in need of advice. Comparing the two periods 1969-1973 and 1974-1978, however clearly demonstrates an improvement in Latin-AM, where the number of totally unacceptable results was reduced from 42 to 21% and the good results increased from 36 to 59%. Similarly, the situation has improved in SEA. In EM the results in the second period worsened because the programme concentrated on those countries and RTIs most in need of improvement. This region also demonstrates the need for locally given expert advice.

The values for various countries demonstrate the even greater differences between countries; the figures refer to the whole period 1969-1978. Country (g) for example shows 88% good results and the rest of 12% were "dropouts" (>10% deviation), (total no.of sets distributed is, however, very small). Another country of the same region (h) has nearly one-half dropouts and only one-quarter good results. One highly industrialised country of EU has 4/5 good results but still has 15% dropouts.

An evaluation is given in the last three lines of Table 4 of the results of intercomparisons obtained with the repeated participation of institutes which once or several times did not return the TLD (N average). In line "N before N" the results of the participation preceding the "N = n.r. etc." (as far as available) were evaluated. The distribution of values within the various classes belongs to the lower quality distribution, those "after N" are a bit better, those "before N" a bit worse. Final conclusions cannot, however, be drawn from these observations.

These examples demonstrate that there is no region and practically no country in the world which does not need to make continuous efforts to get accurate clinical dosimetry applied in all radiotherapy institutions, even if in the majority of institutions the standard is high.

One occasionally hears the argument that a deviation in dose from the international standard does not matter as long as it is consistent within the institute; in other words if the deviation is the same and in the same direction (plus or minus) over the years, then the institute would apply its own empirically found therapeutic dose. This argument is not considered valid in the opinion of most experts. Nevertheless, it was thought to be of interest to check the consistency of results of institutes participating more than once in the intercomparisons. The data are presented in Table 5. 205 RTIs or 49% of the total 416 participated more than once; of these, 66 twice, 45 three times and 94 four and more times. The table shows the percentage of the institutes in the relevant column belonging to five classes of consistency ranging from 5% to more than 40%. The relevant class means that the highest measured deviation differs from the lowest measured by the percentage indicated by the class. Class A, for example includes differences from 0% (e.g. +A +A for the "highest" and "lowest" deviations, or +B +B, or -C -C etc.) up to 5% (e.g. +A -A, or +B ±0, or -C -B etc). Class B includes e.g. +A -B, or +B -B, or ±C ±0 etc. and so on. The values quoted in brackets (...) indicate the percentage of institutes in the relevant column for which the difference of highest and lowest deviation does not include the ±5% class of deviation from IAEA measurement and all deviations are either in the plus or minus direction. In column "twice" for example 35% of the 66 institutes in class A, which could e.g. be +A -A or -B -C etc. (18)% outside the ±5% class therefore are +C +B or -B -C pairs, 35-18 = 17% are +A -A, or +B ±0 and similar.

Considering all 205 institutes together it is remarkable that only 19% of them are consistent in their dosimetry within 5% and only 13% of them (19-6) are also in agreement with the international standard. 55% of them (class C to E) demonstrate differences in their applied dose of more than 10%. The statistics of consistency are much better for those which participated twice or three times only. This is easily explainable for two reasons: (1) The increased numbers of participation increase the chance of detecting errors occurring randomly rather than systematically. (2) Institutes with bad results were usually requested to participate again in the next batch. In judging the results one should not forget in addition that the higher classes C to E also include those institutes which first showed bad results and then improved. This evaluation anyhow demonstrates the invalidity of the argument that consistency of dosimetry in an individual institute is more important than accuracy in relation to standard. Institutes which were consistent (class A, perhaps also B) were usually also good in relation to the standard; those deviating from the standard were almost all also bad as regards consistency.

3. Conclusions

3.1 The situation regarding the accuracy of clinical dosimetry still requires considerable efforts in practically all WHO Regions and in almost all countries to ensure that the existing radiotherapy services, particularly in developing countries, but also in industrialised ones, deliver accurate tumour therapy which is essential if it is to be effective. The IAEA/WHO Network of Secondary Standard Dosimetry Laboratories (SSDLs) should obtain increased support and strengthening by national and international authorities in order to enable it to become fully operational and effective in the shortest possible time, and particularly to fulfil its advisory and educational functions on a worldwide basis.

3.2 It is considered desirable that it be included in codes of practice or even made compulsory by national authorities for any radiotherapy institute involved in cancer therapy with high energy radiation to regularly - say once a year if the results are good; more frequently if not acceptable deviations are observed - participate in a postal dose intercomparison similar to that organized by IAEA/WHO. The SSDLs should be stimulated and supported in organizing such national or regional intercomparisons. For the time being also the IAEA/WHO Services can be used for that purpose. Services offered by SSDLs should, as an additional safety measure, be regularly intercompared on the international level, and this could perhaps be organized by the Network.

3.3 Services of short-term consultants should be made available at relatively short notice to RT institutions which cannot manage to solve their problems by themselves. Experts from WHO Collaborating Centres and SSDLs should increasingly be appointed for such missions.

3.4 The training of radiotherapy staff, including physicists, radiotherapists and medical radiological technicians, in clinically applied dosimetry should be strengthened and short, practically oriented training courses organized on a national or regional basis, wherever an increased frequency of bad results is observed in a country or region.

3.5 The above recommendations do not conflict with, but rather complement, WHO's priorities in the field of Primary Health Care, as it would be ethically unacceptable to establish Primary Health Care, one of whose aims is the early detection of cancer, without establishing or bringing existing health services for cancer treatment to a stage of development and competence where they can effectively treat cancer patients. Reference is made in this context to the report of a WHO Meeting of Investigators on the Optimization of Radiotherapy particularly in developing countries held in Cambridge, UK from 11-15 September 1978. It is expected that this report will be published during 1979.

Table 1 - Distribution of TLD 1969-1978

Batch No.	Date	Number of Sets to Region AF	AM	EM	EU	SEA	WP	TOT.	n.r. etc.*
I°	July 1969)	Partially			(Not all results available				
II°	October 1969)	included			as trial done by IAEA				
III°	December 1969)	in I-III			alone).				
I	April 1970	5	2	6	36	5	6	60	18%
II	August 1970	-	15	9	18	22	4	68	10%
III	December 1970	3	38	1	12	12	8	74	12%
IV	April 1971	-	3	12	21	6	-	42	12%
V	July 1971	-	6	2	9	8	14	39	8%
VI	November 1971	-	1	-	1	1	37	40	40%
VII	March 1972	-	-	2	35	-	-	37	8%
VIII	July 1972	-	5	20	9	7	-	41	27%
IX	January 1973	-	-	3	17	-	22	42	14%
X	May 1973	-	-	-	14	10	10	34	6%
XI	October 1973	-	11	8	7	7	5	38	21%
XII	January 1974	-	20	2	-	1	18	41	20%
XIII	May 1974	-	11	-	-	1	11	23	0%
XIV	October 1974	-	16	12	3	5	-	36	39%
XV	April 1975	-	19	-	8	-	12	39	10%
XVI	August 1975	-	15	-	1	-	21	37	16%
XVII	March 1976	-	8	18	-	-	18	44	11%
XVIII	August 1976	-	1	15	8	24	-	48	31%
XIX	December 1976	-	10	-	1	21	-	32	9%
XX	May 1977	-	17	16	-	34	10	77	9%
XXI	November 1977	-	9	15	-	35	10	69	6%
XXII	July 1978	-	-	15	4	28	3	50	6%
XXIII	September 1978	-	(Not yet available, November 1978)						
TOTAL		8	207	156	204	227	209	1011	15%

* = not returned, or not irradiated, or not evaluable due to mistakes in handling the TLD by the Institute.

Table 2 - Other Data split by Regions

	AF	AM	EM	EU	SEA	WP	TOTAL
Sets distributed	0.8%	20.5%	15.4%	20.2%	22.5%	20.7%	100%
Sets n.r. etc.	0%	13%	16%	9%	18%	21%	15%
No. of Countries part.	2	20	13	17	7	11	70
No. of Institutes part.	7	121	38	115	60	75	416
Inst. part. 1 time	86%	66%	24%	57%	48%	27%	50%
2 times	14%	13%	13%	22%	12%	23%	17%
3 times	-	9%	8%	15%	2%	23%	12%
4 times	-	8%	11%	4%	2%	15%	7%
5 times	-	2%	13%	2%	3%	8%	4%
5 + times	-	2%	32%	1%	33%	5%	10%

Table 3 - Not returned (n.r. etc.) Sets
Split according to frequency of participation

Participation (times)	1	2	3	4	5 +	TOTAL
No. of Inst. n.r. once	30	20	11	5	21	87
	= 14%	= 14%	= 7.5%	= 4%	= 23%	= 21%
No. of Inst. n.r. twice	-	4	5	9	7	25
		= 3%	= 3%	= 7%	= 2%	= 6%
No. of Inst. n.r. three and more times	-	-	0	0	8	8
					= 24%	= 2%

Table 4 - Results of TLD Intercomparisons

WHO REGION	PERIOD	CLASS A ±2%	A + B ±5%	A+B+C ±10%	D to G > ±10%	E to G > ±20%	F + G > ±50%	No. of Countries	No. of Inst.	No. of sets distr.	Of these n.r. etc.
AF *	I	25%	63%	100%	-	-	-	2	7	8	0%
LATIN AM	I	14%	36%	58%	42%	13%	2%		56	81	21%
	II	31%	59%	79%	21%	8%	1%		91	126	9%
	I + II	25%	51%	72%	28%	9%	1%	20	121	207	14%
EM	I	24%	60%	76%	24%	2%	-		29	63	21%
	II	27%	48%	67%	33%	4%	-		30	95	13%
	I + II	26%	53%	71%	29%	3%	-	13	38	158	16%
EU	I	31%	73%	90%	10%	3%	-		112	179	8%
	II	25%	50%	85%	15%	-	-		15	24	17%
	I + II	30%	70%	89%	10%	3%	-	17	115	203	9%
SEA	I	30%	52%	70%	30%	7%	-		36	78	22%
	II	24%	58%	87%	13%	4%	0.8%		49	148	16%
	I + II	26%	56%	82%	18%	5%	0.5%	7	60	226	18%
WP	I	34%	55%	82%	18%	12%	1%		64	103	25%
	II	35%	72%	86%	14%	7%	-		57	110	16%
	I + II	34%	64%	84%	16%	9%	0.6%	11	75	213	21%
WORLD TOTAL	I	28%	59%	79%	21%	6%	0.5%		304	512	17%
	II	29%	59%	81%	19%	5%	0.5%		242	503	14%
	I + II	28%	59%	80%	20%	6%	0.5%	70	416	1015	15%

Table 4 - Continued

WHO REGION	PERIOD	CLASS A ±2%	A + B ±5%	A+B+C ±10%	D to G >±10%	E to G >±20%	F + G >±50%	No. of Countries	No. of Inst.	No. of sets distr.	Of these n.r. etc.
	COUNTRY										
LATIN AM	(a)	19%	50%	69%	31%	6%	-	1	29	37	14%
	(b)	33%	65%	79%	21%	9%	-	1	28	47	9%
	(c)	30%	50%	77%	23%	10%	3%	1	27	36	17%
	(d)	30%	50%	60%	40%	10%	-	1	7	12	17%
	(e)	13%	38%	75%	25%	-	-	1	8	10	20%
EM	(f)	32%	68%	86%	14%	7%	-	1	11	35	20%
	(g)	38%	88%	88%	12%	-	-	1	5	10	20%
	(h)	14%	24%	55%	45%	3%	-	1	5	31	6%
EU	(i)	25%	58%	88%	13%	8%	-	1	10	25	4%
	(k)	31%	71%	94%	6%	3%	-	1	24	39	10%
	(l)	31%	77%	85%	15%	-	-	1	26	28	7%
	(m)	20%	53%	80%	20%	7%	-	1	8	19	21%
	(n) *	56%	89%	100%	-	-	-	1	9	9	-
	(o) *	50%	67%	100%	-	-	-	1	6	6	-
SEA	(p)	22%	53%	80%	20%	5%	-	1	44	144	17%
	(q)	36%	64%	82%	18%	-	-	1	5	15	27%
	(r)	34%	72%	86%	14%	7%	3%	1	5	32	9%
WP	(s)	46%	82%	100%	-	-	-	1	11	32	13%
	(t)	37%	60%	79%	21%	10%	1%	1	36	99	31%
	(u)	29%	57%	95%	5%	5%	-	1	7	25	16%
	(v)	27%	58%	69%	31%	15%	-	1	11	30	13%
N average		25%	51%	73%	27%	7%	1%			416	38%
N before N		19%	45%	69%	31%	7%	-			58	
N after N		26%	52%	76%	24%	5%	-			58	

Note: Period I = Batch I° to XI = 1969 to 1973 inclusive
Period II = Batch XII to XXIII = 1974 to 1978 inclusive

N average = Results of all sets distributed to institutes which have once or more times not returned a set.

N before N = Results of sets obtained before a set was not returned.

N after N = Results of sets obtained after a set was not returned.

* Only selected institutes for that country(ies) participated in the first (pilot) batches in order to check the suitability of the intercomparison method.

Table 5 - Results of Repeated Measurements

Participation:		2 times	3 times	4 and more times	Total more than once
No. of Institutes		66 = 100%	45 = 100%	94 = 100%	205 = 100%
Class	No set returned	6%	-	-	2%
A	0-5%	35(18)%	27 (2)%	4 (2)%	19 (6)%
B	6-10%	29 (9)%	36 (4)%	17 (3)%	25 (5)%
C	11-20%	24 (9)%	20(11)%	26(10)%	24(10)%
D	21-40%	2 (2)%	7 (4)%	28 (9)%	15 (5)%
E	>40%	5 (3)%	11 (7)%	26(13)%	16 (8)%
All (% Total)		32%	22%	46%	100%

Values in (..) = % of values outside $\pm$ 5% in absolute terms (i.e. all values of the institute either positive or negative deviations).

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DOSE INTERCOMPARISON PROGRAMME OF THE REGIONAL REFERENCE CENTRE OF ARGENTINA

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Abstract

DOSE INTERCOMPARISON PROGRAMME OF THE REGIONAL REFERENCE CENTER OF ARGENTINA.

This report includes a brief survey of the activities developed in the Regional Reference Center and a description of the TLD teletherapy intercomparison programme based on the original IAEA/WHO studies. Results of an absorbed dose intercomparison of 18 therapy units are presented.

1. INTRODUCTION

The Regional Reference Center of Argentina was established by agreement between the World Health Organization and the Comisión Nacional de Energía Atómica of Argentina in cooperation with the International Atomic Energy Agency, in 1968.

This Regional Reference Center is a Secondary Standard Dosimetry Laboratory that belongs to the IAEA/WHO network. As similar laboratories existing in other countries, it was established due to the necessity of improving the treatment planning in radiotherapy services and increasing the participation of the physicists experienced in this speciality and was the natural step in the developing programmes in radiotherapy physics established at that time in Argentina.

The principal aims of these laboratories are: to calibrate radiation measurement instruments used for radiotherapy and radiation protection; to give advice on radiation dosimetry in clinical work; and to develop a training programme in radiotherapy physics.

In 1975, an agreement with the IAEA was signed in order to develop a postal dose intercomparison programme. It will be explained in detail below.

2. EQUIPMENT, INSTRUMENTS AND PRINCIPAL TASKS PERFORMED

The available irradiation sources at this laboratory are: two X-ray generators (a 10 - 100 kV Seifert with a Philips tube and a 80 - 300 kV Siemens Stabilipan), a telecobalt unit (Picker C4X/60), and smaller Co-60 and Cs-137 sources for health physics instruments calibration.

The principal instruments employed are a secondary standard dosimeter Küstner-Pychlau, two PTW type DUO, a free-air chamber for low energies (made in Argentina), and all the accessories needed to perform the calibration of dosimeters used in radiotherapy and radiation protection.

For thermoluminescent dosimetry, LiF TLD-700 powder is used as detector. A Teledyne Isotopes model 3700C reader is used to evaluate the detectors. The TLD absorbed-dose values are derived from PTW ionization chambers.

This Center has also a laboratory for chemical dosimetry.

The most important tasks developed up to now are:

(a) Dosimeter calibration. Since 1971, 430 calibrations of radiotherapy instruments and 140 calibrations of radiation protection instruments were performed.
(b) Training programme. Since 1964, 19 Dosimetry in Radiotherapy courses have been given. 252 physicians and 18 physicists advisers attended these courses, and some of them took a special training in radiotherapy physics.
(c) Radiation dosimetry advisory work has been performed in several radiotherapy services.
(d) Cooperation with the PAHO in the intercomparison quality-control studies for film badge dosimetry services, made in 1975 and 1977.
(e) TLD intercomparison programme. This will be explained in detail in the next section.
(f) Development of the ferrous sulphate system for high dose measurements. This laboratory has participated in the two IAEA high dose intercomparisons made in 1977 and 1978.

3. THE TLD INTERCOMPARISON PROGRAMME

3.1 Cooperation with the IAEA/WHO Co-60 therapy units intercomparison programme.

Since 1974 the Argentine's SSDL has contributed to the IAEA/WHO Co-60 Teletherapy Dosimetry Service by sending LiF dosimeters to the therapy centers of our country and giving them technical assistance in the experimental procedure for the intercomparison.

Up to 1975 the participants received two sets of capsules containing LiF powder. One set was to be exposed to a specified dose (200 rad). The other set was to be exposed for a specified time (2 min). The results of the capsules irradiated for a fixed time were considered less reliable than those of fixed dose irradiation (Ref. 1). Thus, since 1976 the fixed-dose procedure was adopted. Participants completed a data sheet and provided information on the basic beam output calibration measurements, the geometry of irradiation and the values of various physical factors that they used to estimate the dose rate at 5 cm depth in water.

Table 1 shows the results obtained by the IAEA/WHO for 21 radiotherapy centers of Argentine during the years 1974 to 1977. From 21 intercomparisons (code 619 and 940 are the same center), about 50% have good dosimetry with a deviation less than $\pm$ 5%. Only three centers have a deviation between $\pm$ 5% and $\pm$ 10%. The only center with a deviation greater than $\pm$ 10% (code 619) has improved its dosimetry but the deviation is still greater than $\pm$ 5%.

In 1977 our SSDL started with a thermoluminescent dosimetry programme, in order to develop an intercomparison programme for Co-60 therapy units in the region with the same procedure as is employed by IAEA/WHO.

3.2 Activities at our SSDL

Details of the first measurements at our SSDL were reported to the IAEA in January 1978 (Ref. 2).

In 1977 the cooperation of three radiotherapy centers of Buenos Aires was obtained in order to undertake a pilot intercomparison. These centers had adequate instruments and highly trained hospital physicists. They were selected to assure a good irradiation procedure.

Each center received 6 capsules with LiF powder from the same batch: 3 of them to be irradiated and the others, without previous irradiation, were kept as control. The centers made the irradiation on the same day, and in order to avoid any fading correction the capsules for calibration were also irradiated in our SSDL on the same day. Once the material was returned to our laboratory all the measurements were performed on the same day. The absorbed-dose values assigned by our SSDL to each capsule and the values quoted by each center are compared in Table 2.

TABLE 1. RESULTS OF THE IAEA/WHO INTERCOMPARISON FOR ARGENTINE RADIOTHERAPY CENTERS SINCE 1974

Year	Batch	Code number	MEAN DOSE calculated by IAEA (rad)	MEAN DOSE quoted by participant (rad)	Deviation (%)	DOSE RATE measured by IAEA (rad/min)	DOSE RATE quoted by participant (rad/min)	Deviation (%)
1974	12	578	487,9	500,0	-2,4	89,4	91,0	-1,8
1974	13	619	179,5	200,0	-10,2	27,9	29,9	-6,5
		620	204,0	200,0	+2,0	65,7	64,0	+2,6
		621	196,0	200,0	-2,0	58,5	58,6	-0,3
		622	200,4	200,0	+0,2	84,8	85,7	-1,0
		623	200,9	200,0	+0,5	83,3	82,3	+1,1
1975	14	652	184,5	*	*	57,2	*	*
		653	192,6	200,0	-3,7	125,1	130,1	-3,8
		654	P	P	P	P	P	P
		655	P	P	P	P	P	P
1975	15	703	165,8	N	*	22,5	N	*
		704	204,9	200,0	+2,4	27,6	26,1	+5,5
		706	212,0	200,0	+6,0	20,2	19,5	+3,7
1976	17	818	194,8	200,0	-2,6			
1977	19	908	209,0	199,6	+4,7			
		909	204,6	199,5	+2,6			
1977	20	940	185,0	200,0	-7,5			
		941	197,2	200,0	-1,4			
		942	*	P	P			
		943	191,9	200,0	-4,1			
		944	P	P	P			
		945	182,0	200,0	-9,0			

Note: * No data available
N Data sheet not returned to IAEA
P Other reasons

TABLE 2. RESULTS OF SSDL PILOT INTERCOMPARISON

Center	$\frac{\text{Measured}}{\text{Mean}}$ %	Diff. (%)	Mean (rad)	A (rad)	Deviation (%)
I (Co-60)	100,13 100,13 99,73	0,40	199,55	199,57	-0,01
I (Cs-137)	99,16 100,83 100,00	1,67	203,43	200,05	+1,70
II (Co-60)	99,94 100,38 99,68	0,70	197,08	200,15	-1,53
III (Co-60)	101,12 98,65 100,22	2,47	133,48	142,83	-6,55

Note: $\frac{\text{Measured}}{\text{Mean}}$ % : individual dose values measured for each capsule expressed as % of the mean dose value of all three capsules (readings made by our SSDL).

Diff.% : difference between max and min from three capsules readings as expressed in previous three columns.

Mean: mean dose in rad assigned by our SSDL.

A : dose in rad as quoted by each participating center.

Deviation % : per cent deviation of measured mean of dose (MM) from the quoted dose (A) in regard to quoted dose:

$$\text{Dev.\%} = 100 \cdot \frac{(MM - A)}{A}$$

The percentage deviation of three teletherapy units is less than ± 2%. One center has a deviation greater than - 5%. Nevertheless this center irradiated with a dose lower than the 200 rad required, and beyond the limits of our calibration straight-line. Thus, the random uncertainty of the absorbed-dose value assigned by our SSDL is greater than the uncertainty expected by this method and the percentage deviation obtained has less reliability.

The first national intercomparison was undertaken in 1978 with 12 participating institutions. 14 therapy heads were checked. Each center received four capsules with LiF powder of the same batch, three of them to be irradiated and the other without previous irradiation was kept as control.

It was requested that a 200 rad dose be delivered to the capsules at 5 cm depth in a water phantom. The centers received a very simple questionnaire in order to obtain information about the basic beam output calibration measurement.

The Co-60 units utilized by the participating institutions were of different origin, as can be seen in Table 3. Most of them were calibrated by the Comisión Nacional de Energía Atómica of Argentine at the time of source change. The CNEA uses for these purposes a dosimeter with appropriate chambers calibrated at our SSDL.

The intercomparison results are summarized in Table 4. Of 14 intercompared units, 9 have a satisfactory dosimetry with a deviation lower than ± 5%. Four centers have a deviation between - 5% and - 10%. Only one center delivered a dose lower than that required (beyond - 10%).

TABLE 3. IRRADIATOR TYPES

Code number	Irradiator type	Date of last source's change
110	Theratron 780	April 1975
112	Picker	November 1973
120	Picker	-
121	Picker (Cs-137)	-
122	Theratron C	September 1975
124	Theratron Junior	July 1974
130	Theratron Junior	January 1978
140	Siemens Gammatron II	September 1975
142	Siemens Gammatron III	March 1977
150	Siemens Gammatron II	March 1967
152	Picker	-
160	Theratron Junior	March 1971
180	Theratron	August 1977
190	Whestinghouse	February 1977

NOTE: Except code number 121, all the irradiators are of Co-60.

TABLE 4. RESULTS OF THE FIRST NATIONAL INTERCOMPARISON OF ^{60}Co AND ^{137}Cs EQUIPMENTS

Code number	Readings L1	Readings L2	Readings L3	ABSORBED DOSE as determined by the SSDL Cap. 1	Cap. 2	Cap. 3	MEAN DOSE $\bar{D}$ det. by SSDL	MEAN DOSE quoted by participant	Dev %
110	52,788	51,956	52,598	197,27	194,16	196,56	196,0	200,0	-2,0
112	52,925	52,782	53,084	197,78	197,24	198,37	197,8	200,0	-1,1
120	52,276	53,220	52,411	195,35	198,88	195,86	196,7	200,0	-1,7
121	55,354	54,854	54,525	206,85	204,99	203,76	205,2	200,0	+2,6
122	52,446	52,237	52,065	195,99	195,21	194,57	195,3	200,0	-2,4
124	33,167	33,795	33,764	123,95	126,30	126,18	125,5	125,6	-0,1
130	49,710	49,864	48,837	185,77	186,34	186,24	186,1	200,0	-7,0
140	50,002	50,780	50,797	186,86	189,76	189,83	188,8	200,0	-5,6
142	55,479	54,818	55,089	207,32	204,85	205,86	206,0	200,0	+3,0
150	50,236	49,708	49,900	187,73	185,76	186,48	186,7	200,0	-6,7
152	48,626	48,424	48,132	181,71	180,96	179,87	180,9	200,0	-9,6
160	54,696	*	*	204,40	*	*	204,4	200,0	+2,2
180	27,444	27,005	27,384	102,57	100,92	102,34	101,9	147,5	-30,9
190	54,666	55,726	55,568	204,28	208,25	207,66	206,7	200,0	+3,4

NOTES: Except code number 121, all the irradiators are of Co-60. Code number 121 is of Cs-137.

* = No data available.

3.3 Discussion

The first national intercomparison gave a mean value of 196, 12 rad for the absorbed dose at 5 cm depth, with a relative standard deviation of ± 4,3%. With regard to the prescribed dose of 200 rad, the mean value deviated by - 1,9%.

The intercomparison made by IAEA/WHO from 1974 to 1977 gave a mean value of 197,2 rad for the absorbed dose at 5 cm depth, with a standard deviation of ± 4,4%. The mean value deviates from the prescribed dose of 200 rad by - 1,4%.

3.4 Conclusions

The TLD intercomparison programme is a very important complement to other means employed to improve the accuracy of radiotherapy clinical treatments. From the Argentine experience in TLD intercomparison studies, this programme is useful not only to identify errors and inaccuracy in the clinical delivery of radiation but to create a greater awareness of the need for correct dosimetry in radiation therapy and to improve our contact with radiotherapy centers in our country. Many physicians ask for advisory and calibration services, and the interest in getting better accuracy in dosimetry has increased.

4. FUTURE INTERCOMPARISON PROGRAMME

In the future this laboratory will continue with the TLD intercomparison programme for telegammatherapy equipment in the way indicated above.

The recently initiated similar feasibility study for orthovoltage X-ray units will be followed in order to start the intercomparisons as soon as possible.

As indicated above, the ferrous sulphate system for high doses has been developed and we intend to apply this system to the radiotherapy dose range to carry out intercomparison studies.

The first linear accelerator for radiotherapy has begun to work this year in Argentina, and several others will begin in the near future. For this reason this laboratory wants to study an intercomparison programme for such equipment using both the TLD and the chemical systems.

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EXPERIENCE IN INTERCOMPARISON AT A SSDL FOR ORTHOVOLTAGE AND HIGH ENERGY BEAMS

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INTRODUCTION

With the increasing use of high energy machines such as teletherapy units and high energy accelerators in the various radiotherapy centres in our country, the Secondary Standards Dosimetry Laboratory of the Bhabha Atomic Research Centre is playing an important role in attending to the needs of the dosimetric requirements of these centres. SSDL (Bombay) maintains all the national primary standards for various radiation qualities. These primary standards have been intercompared with similar devices at the International Bureau of Weights and Measures (BIPM), the National Bureau of Standards (USA), the National Physical Laboratory (UK), the Bureau of National Metrology (France) and the Regional Calibration Laboratory (New York) during this decade. The intercomparisons have been carried out using transfer standard Shonka chambers and the results showed congruence better than $\pm$ 1 per cent. The SSDL provides in addition the following services: (1) calibration of Secondary Standard Dosimeters belonging to various centres in India; (2) output calibration of radiation beams for field conditions; (3) in situ comparison of all Institutes' Secondary Standard Dosimeters against SSDL reference standard etc.; (4) organizing postal dose intercomparison programme using TL dosimeters for different types of radiations in collaboration with IAEA/WHO in this geographical region. The procedures adopted by the SSDL for such postal dose intercomparison programmes for teletherapy beams and our plans for the international intercomparison for high energy photon and electron beams and also our experience gained in this field are outlined in this paper.

Since 1976 the SSDL Bombay had been conducting an absorbed dose intercomparison service for ^{60}Co teletherapy units in India, Burma and Sri Lanka. About 70 dose intercomparisons have been conducted so far at 50 radiotherapy centres. The results are summarized in Table 1. It may be seen from the Table that in 69 per cent of the cases, the deviations were within $\pm$ 5%.

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The intercomparisons were repeated whenever deviations exceeded $\pm$ 15%. In most cases a significant improvement in dosimetry was observed on repeat intercomparisons. These intercomparisons had also brought to light some instances of serious errors in the dosimetry practices in some of the hsopitals. Whenever a serious error was detected, immediate follow-up action was initiated, and this was continued until the mistake was identified and rectified. The postal dose intercomparison had thus really averted several potential accidents in radiotherapy. Frequent intercomparisons are very important to assure the hospitals of continued adequacy in their dosimetry and in some cases to detect if any later mistake had developed. Thus the dose intercomparison service is valuable both from the point of detecting serious errors and ensuring uniformity and good quality of radiotherapy dosimetry.

An important extension of radiotherapy dosimetry service is the provision of accurate beam output calibration data for all the teletherapy units because the accuracy in dose calculations mainly depends on the accuracy of beam output value. This programme was initiated and conducted concurrently with the dose intercomparison service by deputing a senior physicist of the SSDL to various radiotherapy centres in the country. In our country, so far, there is no official code of practice specifying how the beam output measurements should be performed. Most of the hospitals measure the beam output in air at SSD + 5 mm. Some hospitals measure the dose directly in a water phantom at 5 cm depth. However, almost every hospital relies heavily on published data (1) for percentage depth dose, back-scatter factor etc., required for absorbed dose calculations. The SSDL was conscious of the fact that the depth dose values are influenced to some extent by machine parameters such as source size, secondary collimator design, penumbra trimmers and radiation field size specifications vis-a-vis optical field etc. Bearing all these things in mind the visiting SSDL physicist performed beam output measurements both in air and in phantom for eventual comparison of absorbed dose in water. The results so far obtained for 50 teletherapy units were analysed (2) and it was found that the absorbed dose value calculated by using the two methods differed by as much as 4% in the case of eight units. Again for these eight units percentage depth dose was measured by exposing TL dosimeters at both 0.5 and 5 cm respectively. The depth dose values differed from those published in the British Journal of Radiology (Supplement 11) by as much as 2.8 per cent (3). The percentage depth dose is an important parameter for clinical dosimetry and should be determined experimentally. The published data may be used for guidance but not for total reliance. This experience led us to another extension of the dosimetry programme namely the central axis depth dose data service by mailed dosimeters. An irradiation stand designed so that TLD capsules could be inserted at eight different central axis locations was mailed to each participant along with an adequate number of TLD capsules depending on the demand by the radiotherapy centre. The irradiated capsules were measured at our SSDL and the results communicated to the user. The depth dose measurement service is entirely independent of the dose intercomparison programme. It is interesting to note that when errors in depth dose

values used in intercomparison were corrected on the basis of the measured depth dose value, the results in some cases have shown significant improvement.

2. Orthovoltage X-ray dose intercomparison

The situation in India as in any other developing country is that the annual growth rate in the number of teletherapy installations is quite rapid while more and more conventional X-ray therapy units are lying in disuse for obvious reasons. Hence the need for X-ray intercomparison is not so keenly felt as in the case of ^{60}Co teletherapy. However, the SSDL, Trombay had worked out two methods for quality determination by TL ratio - namely (1) central axis depth dose ratio and (2) external filtration. Both the methods have been proved to be independent of X-ray spectrum for a given first HVT. They have been successfully used in preliminary dose intercomparison experiments conducted for superficial and deep X-ray therapy at a local hospital.

The most important factor that must be considered in this context is the large fluctuation in X-ray beam intensity due to main voltage variation in many of the cities. From our experience we have noticed that it is not uncommon in routine output measurements that a set of 5 successive output measurements each of 2-3 minutes duration showed variations as much as $\pm$ 10%. It is impossible to rely on a statement of delivered dose unless the X-ray unit had incorporated a monitor chamber system. This point is very important in X-ray therapy dosimetry, particularly when a recommendation has to be made to a hospital on the factors that caused larger deviations. To the best of our knowledge none of the X-ray therapy units in India had built-in dose monitors. In view of this, the programme to initiate regular dose intercomparison service to hospitals was deferred in favour of developing a reliable and simple monitor system for eventual large scale supply to hospitals. The SSDL has succeeded in developing a small ionization chamber that can be positioned near the space provided for filters.

HVT is an important parameter in X-ray dosimetry. The measured value of HVT depends on the conditions of geometry, purity of filters, energy dependence of detectors etc. Except for purposes of using published depth dose data, the HVT value is not required in dosimetry. Instead of HVT in aluminium or copper, half value depth in water would be a better specification of beam quality. We think that the most appropriate dosimetry service for orthovoltage X-rays should be for central axis depth dose values using mailed TL dosimeters. The HVT as well as the absorbed dose at a specified depth (5 cm) can be obtained simultaneously besides the central axis depth dose data.

3. Dose intercomparison for Megavoltage X-rays

A large number of medical accelerators used in the world belong to the less than 10 MV photon energy category (4). To encourage participation of many hospitals, the dose intercomparison service may be restricted to 6 MV only for the time being. Another advantage of choosing 6 MV is that the existing ^{60}Co dosimetry service can be extended easily. LiF powder encapsulated in nylon is adequate at this energy. A check on the beam energy is very

important to avoid errors in dosimetry and this can be done by depth dose ratio check. Since the accepted calibration depth up to 10 MV is 5 cm, two dosimeters may be located at 5 cm and 10 cm depths and irradiated simultaneously. The dose intercomparison service may be extended to higher energies if necessary in a progressive manner. The depths at which dosimeters should be located must be the same as the calibration depths recommended by ICRU 23 i.e. 7 cm up to 25 MV and 10 cm beyond.

4. *Dose intercomparison for high energy electrons*

IAEA and many other standard laboratories have been conducting electron beam dosimetry service by mailed Ferrous Sulphate dosimeters and valuable experience has already been gained on the reliability of this service. There is no need for the IAEA to discontinue this service and find another substitute for FRICKE. The FRICKE system is recognized as a secondary standard and proved to be stable and reliable for mailed dosimetry. From the point of convenience the intercomparison service should be restricted to one electron energy, say 20 MeV, and the depth of measurement should be in the region of dose maximum (1.5 cm).

An energy check measurement must be a part of the dose intercomparison. This check can be done by irradiating another dosimeter at 3.5 cm depth simultaneously.

In conclusion, it must be said that absorbed dose intercomparisons have proved extremely valuable in improving the quality of radiotherapy with ^{60}Co and orthovoltage beams. It is only appropriate to extend the programme to include high energy photon and electron therapy. For the sake of completeness, ^{137}Cs teletherapy must also be included in the dose-intercomparison.

Table 1

Results of Postal Dose Intercomparison

Batch	Total Institutes who returned capsules	$\pm$ 5%	5%	10%	15%
1	5	3	2	-	-
2	8	5	3	1	-
3	10	5	5	2	1
4	9	7	2	-	-
5	15	8	7	3	3
6	22	15	7	5	3
Total	69	43	26	11	7
100%		62%	38%	15.5%	10%

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BUREAU OF RADIOLOGICAL HEALTH ACTIVITIES IN DOSE DELIVERY SURVEYS

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1. The Bureau of Radiological Health(BRH) is part of the Food and Drug Administration of the United States of America and is responsible for the safe and effective use of radiation from electronic products and radioactive material. Licensing the use of radioactive by-product material remains the responsibility of the Nuclear Regulatory Commission.

2. Between 1974 and 1977 the BRH contracted with the National Bureau of Standards (NBS) of the United States to conduct a dose delivery survey of the cobalt-60 teletherapy units in the US. This was similar to the IAEA postal dosimetry service, but on a one time basis.
   a) About 110 units out of about 1000 units were surveyed.
   b) 83 % yielded dose interpretations within 5 % of the prescribed dose.
   c) 13 % yielded difference between 5 % and 10 %.
   d) 4 % of the dose interpretations were greater than 10 % for the dose requested.
   e) NBS Technical Note 978 is a publication reporting the results of the survey to BRH and others.
   f) BRH is conducting an analysis of the survey and will publish its conclusions by late summer 1979.
   g) An "Interim Report of the National Bureau of Standards/ Bureau of Radiological Health ^{60}Co Teletherapy Survey" by Thompon, Wyckoff and Soares appeared in Int. Journal of Radiation Oncology, Biology and Physics,(Vol 4 pp-1065-1068 Nov- Dec 1978).

3. BRH is planning a mailed dose delivery survey of medical linear accelerators with photon energies from 4 to 10 MeV.

   a) NBS will evaluate and calibrate a lucite phantom containing LiF - TLD chips.

b) BRH will conduct the survey probably using LiF - TLD chips because of considerable experience in handling large number of these chips in surveys of dental and mammographic X-ray units.

c) An advisory group from the Radiation Therapy Committee of the American Association in Medicine is assisting in the design and selection of the dosimetry system and will help to plan the survey questionnaire.

d) The survey is expected to ask for the dose to be delivered to a depth of 10 cm in a $(20\ cm)^3$ lucite phantom and for the calculation and constants used in arriving at that dose. This will provide more data than a simple dose intercomparison in that it will also check the ability to deliver a prescribed dose under patient-like conditions.

e) Site visit follow-up is planned in cases where serious dose delivery difference is found.

1) The serious difference "level"has not been defined.

2) The method of follow-up has not been decided.

Possibilities include:

a) Hiring private consultants.

b) Forming an agreement with the six Centers for Radiological Physics which are sponsored by the National Cancer Institute and coordinated by the American Association of Physicists in Medicine.

f) It is planned to offer the available TLD dose delivery assessment as a continuing programme that could become part of a facilities comprehensive quality assurance program.

4. My reasons for attending this meeting are that the questions the IAEA needs to answer for an intercomparison of medical linear accelerators of its members, the BRH needs to solve for a similar survey of the United States.

Further, if both agencies choose the same or compatable survey methods, we both will have an expanded data base.

STATUS OF RADIATION THERAPY IN NIGERIA AND PROBLEMS OF ACCURATE DOSIMETRY

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Abstract:

The status of radiation therapy in Nigeria, a developing nation, and high-lights of cancer incidence in Nigerians are presented. The need to develop radiotherapy, and its place in relation to other modalities of cancer management in developing nations are examined. Finally, the numerous problems of radiation dosimetry typical of some developing nations are stressed. In Lagos we place emphasis on the $FeSO_4$ dosimetric system for the most reliable results.

In view of the numerous weighty problems in developing nations, there is need for a continious input from the developed nations in order to build-up the most effective radiotherapy centres.

Introduction

(1) It is difficult to discuss the Status of Radiotherapy in Nigeria and the Problems of Accurate Dosimetry without a few words about the pattern.. of cancer incidence in the country.

In addition to the established facts and speculations in respect of cancer incidence - racial, sex, age etc., and aetiology in man - genetic, environmental, viral, etc. an important finding worth stating is that, the over-all crude incidence of cancer over the last several decades in Nigeria, is significantly lower than that in Europe, and the U.S. (Doll et al. 1966). Cancer incidence surveys in Nigerians (Edington and Maclean 1965) and our experience in Lagos over the last decade in which our Radiotherapy center has been functional, confirm this trend. Virtually, all types of cancer seen in caucasians have

been recorded in Nigerians but prevalence of specific types differ. The only Radiotherapy centre in the region is in the city of Lagos, population 3 million. This centre receives cases of cancer referrals from all over Nigeria (population 90 million) and also from neighbouring countries, the Camerouns, Ghana, and Sierra Leone.

In discussing the incidence of cancer in Nigeria we cannot but mention a few unusual findings which may have some implications for the general cancer effort.

(a) Primary cancer of the lung and liver are linked respectively to smoking and excessive alcohol consumption amongst other causes. Both practices in Nigeria for economic and other reasons are indulged in to considerably lesser extents than amongst the developed nations. The incidence of primary lung carcinoma in Nigeria is unusually low, - only three cases amongst some 1,000 cancer patients seen in Lagos. Liver cancer incidence on the other hand is reported higher than amongst caucasians.

(b) Another occurrence is the unusually low incidence of cancer in the aged in Africans, Davies et al. (1962) - considerably less than in caucasians - it would appear that those who escaped the multitudinous infections and disease afflictions in childhood and middle age develop enough resistance to combat cancer in old age.

(c) A common occurrence in both caucasians and Nigerians is that the incidence of Ca-Breast and Ca-Cervix is high. Indeed about 2 out of 3 women treated for cancer in our radiotherapy department are either afflicted by Ca-Breast or Ca-Cervix.

(2) Radiotherapy Centres in Developing Nations

The problems encountered by developing nations in respect of effective application of radiation in therapy are manifold; where facilities are available e.g. in Lagos, we find problems of

(a) lack of supporting technical personnel for effective maintenance and service of teletherapy machines.

(b) mulish ignorance of administrative staff and consequent inertia in financing progressive programmes in the areas of training and acquiring of accessory equipment.

(c) with a one man band therapist, possibly one trained a couple of decades back, and limited clinical interactions with other radiotherapists, chances of optimisation of radiotherapy service are not enhanced.

(d) the status of the general medical service which is remotely tied up to the level of cancer consciousness of the populace could affect cure rates; for instance, the over-all survival of our cancer patients in Lagos, would be improved if the rather high proportion of cases reporting for the first time in our clinics did not come too late for any but a palliative form of treatment.

(e) to add problems of inadequate dosimetry to the above list, would be disastrous.

(3) The Radiation Therapy Division in Lagos:

The Radiotherapy section Lagos is part of a compact Radiation Centre, which incorporates a Radiation Biology section, Nuclear Medicine service and a Medical Physics unit. Our radiotherapy division is a small one by all standards, it is equipped with a ^{60}Co Theratron 80 unit, 2 orthovoltage X-ray machines, and a superficial X-ray unit. On the average, in a good year of minimal technical problems, roughly 300 new patients are treated, the others unfortunately are turned away: this is inevitable in view of the number of countries and the mammoth sized population served by the centre.

(4) The Problem of Dosimetry in Lagos

The problems of dosimetry in Lagos are considerable, and the need for a Secondary Standards Dosimetry laboratory cannot be over estimated especially in view of plans to establish new therapy centres not only in Nigeria but in neighbouring countries as well.

Firstly, the performance of the commercial thimble chamber over a long period in Lagos is subject to fluctuations owing to high humidity and temperature conditions. Kia Boon and colleagues in Singapore a town with high humidity, and similarly low lying tropical conditions as Lagos, reported the interference of fungal growths as well (personal communication). They have, by proper air purification and temperature control (not conventional air conditioning)

established reasonable storage conditions and consequently improved their ionisation chamber performance.

In Lagos we rely extensively, on the $FeSO_4$ dosimetric system which is not affected by high humidity and fungal growth. Furthermore, we have for use as standards a pre-calibrated (NPL) ^{90}Sr source, and our ^{60}Co machine of predictable output. These ensure independent checks on our ionisation chamber measurements. By and large, we are confident that the prescribed doses in contradistinction to the ideal ones - if any one knows what is ideal - are delivered to the tumour.

One may pose the question, is the introduction of radiotherapy departments into developing nations justifiable? Skeptics may argue the importance of other priorities in health care in these emerging nations e.g. the scourge of infectious diseases; problems encountered are numerous and weighty, e.g. lack of trained personnel to successfully execute the specialised damands of this sophisticated arm of modern medicine etc. However, looking in depth, would reveal a pressing need for the benefits of a radiotherapeutic service, even if it be of a modest size.

(5) In conclusion may I state the following,

(i) Cancer research and treatment in developing nations should be encouraged not only because of their benefits to these nations, but also the possible benefits that the over-all cancer effort may derive from this completely different dimension; differences in geographical distribution pattern of cancer, e.g. Burkitt's lymphoma in Africa; variations in incidence, and age dependence, which could lead to a modification of, or evolution of new concepts in the aetiology and treatment of cancer.

(ii) Dosimetry in developing nations, is confounded by numerous factors, and cooperation with the larger centres in the developed nations can only enhance performance.

(iii) Radiotherapy in developing nations is at its infancy and may be nurtured fully only through the input of both economical, technological and human resources from the better developed nations.

(iv) In view of the acknowledged advantages of radiotherapy over other modalities in the treatment of certain types and forms of cancer, and obvious general limitations in developing nations, in these areas as well, e.g. experienced manpower, facilities in the effective administration and follow through of chemotherapy and even surgery, in cancer management, a well developed and properly dispensed less traumatic radiotherapeutic service has a lot to commend it in developing nations.

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USE OF THE FERROUS SULPHATE DOSIMETER AS TRANSFER INSTRUMENT FOR CALIBRATING CLINICAL DOSIMETERS

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1 - INTRODUCTION -

In clinical dosimetry, the basic physical parameter is the reference absorbed dose which determines the treatment durations and consequently the doses delivered to the patient. It has been shown, through systematic clinical observations, that discrepancies of only 10 % between doses delivered to tumours in identical treatments led to significant clinical differences, thus leading radiotherapists to wish for dose estimations with reproducibilities of 1 % and accuracies of 3 % [1]. Such constraints imply the use of a reference dosimeter of high quality and correctly calibrated.

Considering that dosimetric primary standards at national laboratories are usually defined with overall uncertainties close to 1 %, and that transference of knowledge through calibration of an instrument inevitably deteriorates accuracy, it is obvious that the operation of calibrating, in dosimetry, is a delicate one and must be carried out with particular care. Note that this is seldom the case in other fields of metrology where the levels of accuracy between primary standards and field measurements differ often by several orders of magnitude. Moreover, the increasing utilization of accelerators in radiotherapy has enhanced the need for calibrations in terms of absorbed dose to tissue (or tissue-equivalent materials such as water). Such calibrations can be deduced from a calibration in terms of exposure by applying appropriate conversion factors (C_λ's [2], C_E's [3]) ; but recent thorough analysis of these factors [4] have shown that their values could lead to errors of several percent , and, besides, even with correct factors, this procedure is not able to take into account the actual irradiation conditions in which the calibrated dosimeter is to be used. Therefore, the best solution consists of calibrating the dosimeter directly in terms of absorbed dose and in the user's beam, provided that an appropriate transfer instrument is chosen.

It is this last procedure which has been retained and recently put in place in the French Calibration Chain [5]. The transfer dosimeter chosen is the ferrous sulphate dosimeter and the calibration conditions were agreed upon following thorough discussions with medical physicists. The procedure is applicable to γ-rays from cesium-137 and cobalt-60 and to X-rays of maximum energies greater than 2 MeV, and to electrons with initial energies between 10 and 35 MeV.

2 - CHARACTERISTICS OF THE FERROUS SULPHATE DOSIMETER -

The transfer dosimeter is a sealed glass ampoule containing the ferrous sulphate solution (see fig. 1).

2 - 1 - Solution container -

The container is a pyrex-glass ampoule of cylindrical shape, with 1.5 mm walls, an outside diameter of 1.7 cm and a height of 6 cm.

In order to avoid spurious oxidation while sealing the container, the solution is frozen by liquid nitrogen during this operation.

2 - 2 - Ferrous sulphate solution -

As the standard Fricke dosimeter, the solution consists of :

1 m mol.l^{-1} $\left[Fe\ (NH_4)_2\ (SO_4)_2\ ,\ 6\ H_2O\right]$

0.4 mol.l^{-1} H_2SO_4

dissolved in air-saturated distilled water.

The distilled water is prepared in three stages : a normal distillation and two slow evaporations in quartz equipment using infra-red heating.

Because of its great sensitivity to organic impurities the solution must be prepared and handled with particular care. All glass vessels are cleaned with a strong oxidizing solution and pre-irradiated with doses of several kilograys. The water used for rinsing is the same as that used for preparing the solution.

2 - 3 - Dosimetric parameters -

Variation of the ferric ion concentration in the solution, due to irradiation, is determined by means of the absorbance variation of the solution measured by spectrophotometry, according to Beer-Lambert's law. Thus the absorbed dose in the solution, D_{sol} in grays, is obtained by the classical formula :

$$D_{sol} = 9.649 \times 10^6 \times \frac{\Delta d}{\varepsilon . \rho . l . G.} \times k_\theta \qquad (1)$$

where

ε / (mol.l^{-1})$^{-1}$.cm^{-1} is the molar extinction coefficient for ferric ions at the wavelength used for the optical density measurement (λ= 303 nm in our case), minus that for ferrous ions, at the reference temperature (25°C).

ρ/g.cm^{-3} is the density of the solution at the reference temperature (25°C).

l /cm is the optical pathlength of the spectrophotometric cell.
(l = 1 cm ± 0.05 %)

G / (ferric ions).(100 eV)$^{-1}$ is the radiochemical yield of the ferrous sulphate solution.

Δd is the difference in optical density between irradiated solution and blank, measured at an actual temperature θ usually slightly different than the reference one $\theta_o = 25°C$.

k_θ is the correction factor for temperature :

$$k_T = 1/\left[1 + \alpha \ (\theta - \theta_o)\right] \qquad (2)$$

with θ, θ_o in $^\circ C$ and α in $(^\circ C)^{-1}$.

Before utilization of the ferrous sulphate dosimeter for calibrations, different properties and characteristics of the dosimeter as well as those of the spectrophotometer have been studied. Among them, the values of ε, ρ, α have been determined :

$$\varepsilon = 2163 \ (mol.l^{-1})^{-1}.cm^{-1} \pm 0.1 \ \%$$

$$\rho = 1.024 \ g.cm^{-3} \pm 0.1 \ \%$$

$$\alpha = 0.66.10^{-2} \ (^\circ C)^{-1} \pm 1.5 \ \%$$

Concerning the G value, which depends on the radiation quality, the following convention has been adopted with users : until the end of the experiments carried out at LMRI and at other foreign laboratories for the determination of G values in high energy photon and electron beams, a constant value of G is adopted [5] :

$$G = 15.6 \pm 0.25 \ (Fe^{+3} \text{ ions}). \ (100 \text{ eV})^{-1}$$

This convention, though perhaps leading to false reference doses, enables however comparisons between hospitals throughout the country. Nevertheless, this assumption shouldn't be too bad if one considers the G values indicated in ICRU reports [2, 3].

3 - TRANSFER PROCEDURE -

3 - 1 - Principle -

The calibration is performed in the user's beam, in conditions as close as possible to the usual ones (this is of particular importance for accelerator beams). The dosimeter to be calibrated and the transfer dosimeters are successively irradiated under identical conditions, i.e. for the same incident beam and at the same position in a reference water-equivalent phantom.

The reference quantity is absorbed dose to water, D_W/Gy ; the calibration factor, $F/Gy.(\text{unit of dosimeter reading})^{-1}$, is given by

$$F = (D_W.M_D^{-1}) \ / \ (R.M_R^{-1}) \qquad (3)$$

where R is the dosimeter reading, corrected for dependence on temperature, pressure, humidity, recombination, etc...

M_D and M_R are the monitor readings, corrected if necessary as above; in the case of a Cobalt-60 or a Cesium-137 beam the monitor is simply a time measuring device.

The reference dose to water D_W is obtained from the dose D_{sol} measured in the ferrous sulphate solution (relation 1) by applying a factor k_p correcting for the perturbation due to the size of the volume of solution and to the glass container :

$$D_W = D_{sol} \cdot k_p \qquad (4)$$

For the same reasons as for the choice of the G value, k_p is conventionally taken equal to unity until its experimental determination.

3 - 2 - General conditions -

Some of the calibration conditions are standardized, they are presented in table 1.

PHANTOM	- dimensions : 30 x 30 x 10 (cm) - water-equivalent composition : 94 % polystyrene 2-5 % polymerization oil 1-3 % T_iO_2 - density : 1.03 $g.cm^{-3}$
REFERENCE DEPTH : 2, 3, 4, 5, 6 cm	
FIELD SIZE : 10 x 10 (cm)	
DOSE TO BE DELIVERED : 50 to 100 Gy	

Table 1 : Standardized calibration conditions

The water-equivalent phantom is composed (see fig. 2) of five parts : F, f, A', B. The main part F contains a cavity into which the other elements fit. The whole constitutes a homogeneous parallelepiped, except for element f which contains the dosimeters. For a given beam quality, the reference depth is obtained by ordering the elements f, A, A', B. (see fig. 3)

For each calibration, three elements "f" are provided :

- two containing each three ferrous sulphate dosimeters (see fig. 4) : one for irradiation, the other for blank,
- one for irradiation of the dosimeter to be calibrated.

3 - 3 - Particular conditions -

The source-to-phantom-surface distance is chosen by the user. The reference depth depends on the beam quality :

- for cobalt-60 and cesium-137 gamma-rays and for 2MV X-rays, the recommended reference depth is 5 cm.
- for photons of higher energies and for electrons of energies between 10 and 35 MeV, the recommended reference depth is the depth corresponding to the dose maximum, which has to be determined by preliminary measurements.

3 - 4 - Uncertainties -

The uncertainty of the calibration factor F depends of course on the uncertainties on the readings of the dosimeter to be calibrated and of the monitor. Concerning the reference dose to water D_W, the estimated upper bound to the systematic uncertainty is 1.9 % (linear sum of individual uncertainties) and the random uncertainty is usually of the order of 0.4. %.

4 - RESULTS AND CONCLUSION -

Thirty-two calibrations have been performed up to now. All dosimeters were of the same type (Nuclear Enterprise, Ionex 2500-3, 0.6 cm^3 chamber), and had previously been also calibrated in terms of exposure for cobalt-60 gamma-rays. Hence, it is interesting to consider, for each chamber and for the different beam qualities, the quotients C' of the dose calibration factors by the exposure calibration factor. The values of C' are presented in table 2 for photons and table 3 for electrons, along with indications on experimental conditions and, for comparison, with the ICRU recommended values of C_λ and C_E [2, 3].

For photons, it can be seen that C' and C_λ are identical for cobalt-60 gamma rays and for 5.5 MV X-rays and that important discrepancies appear for higher energies (the mean value of the quotient C'/C_λ rises to 1.06). In addition, the effect of the correction for recombination in the chamber (less than 1 %) doesn't modify the discrepancies.

For electrons the differences between C's and C_E's, particularly at high energies, seem to depend mainly on the corrections for recombination, which in these cases rise to several percent ; over 13 MeV, the mean values of the quotient C/C_E are 1.00 if these corrections have been applied and 1.04 if not.

As a conclusion, this transfer procedure provides more information than only the calibration factor, because all irradiations and measurements with the dosimeter to be calibrated are performed by the user in his beam, and in the case of accelerator beams, the influence of monitoring is taken into account as well as the quality of the preliminary measurements necessary for

photon quality	number of C' values	dose rate $_{rad\ .min^{-1}}$	depth in phantom, cm	correction for recombination	C' $_{rad.R^{-1}}$	C_λ (ICRU) $_{rad.R^{-1}}$	C'/C_λ
^{60}Co γ	7	50 - 200	5	no	0.95	0.95	1.00
5.5. MV X	1	230	6	no	0.95	0.94_5	1.00
9 MV X	1	250	2	no	0.95	0.93	1.02
18 MV X	1	400	4	no	0.97	0.91_5	1.06
25 MV X	5	170 - 200	5	no	0.98	0.90	1.09
"	1	140	5	yes	0.94_5	0.90	1.05
"	1	200	3	yes	0.98	0.90	1.09
27 MV X	1	40	4	yes	0.96	0.90	1.07

Table 2 - comparison of C' values resulting from calibrations of dosimeters and C_λ values given by ICRU-Report 14 [2] (for convenience, quantities are expressed in non-SI units).

electron beam energy MeV	number of C' values	dose rate, $rad.min^{-1}$	depth in phantom cm	correction for recombination	C' $rad.R^{-1}$	C_E (ICRU) $rad.R^{-1}$	C'/C_E
10	2	180/260	2	no	0.90	0.89	1.01
"	1	200	2	yes	0.88	0.89	0.99
"	1	245	2.5	no	0.90	0.90	1.00
13	1	50	2	yes	0.87	0.87	1.00
"	2	200/220	3	no	0.93	0.90	1.03
16	2	170/210	3	no	0.89_5	0.87	1.03
19	1	210	4	no	0.90	0.86	1.05
"	2	200	4	yes	0.86_5	0.86	1.01
"	1	200	5	yes	0.86	0.88	0.98
30	1	150	2	yes	0.82	0.81	1.01

Table 3 - Comparison of C' values resulting from calibration of dosimeters and C_E values given by ICRU-Report 21 [3] (for convenience, quantities are expressed in non-SI units).

the choice of the reference depth. All informations relative to experimental conditions and measurements is given by the user in the official document sent back to the Calibration Center. After analysis of this document and reading of the ferrous sulphate dosimeters, the calibration factor is established by the Calibration Center.

Because of this distribution of tasks and responsabilities, a good co-ordination is necessary between the user and the Calibration Center. Moreover, this procedure constitutes a technical assistance service, since through the relations with hospital physicists, many dosimetric problems are dealt with.

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Fig. 1 - View of the sealed glass ampoule containing the ferrous sulphate solution

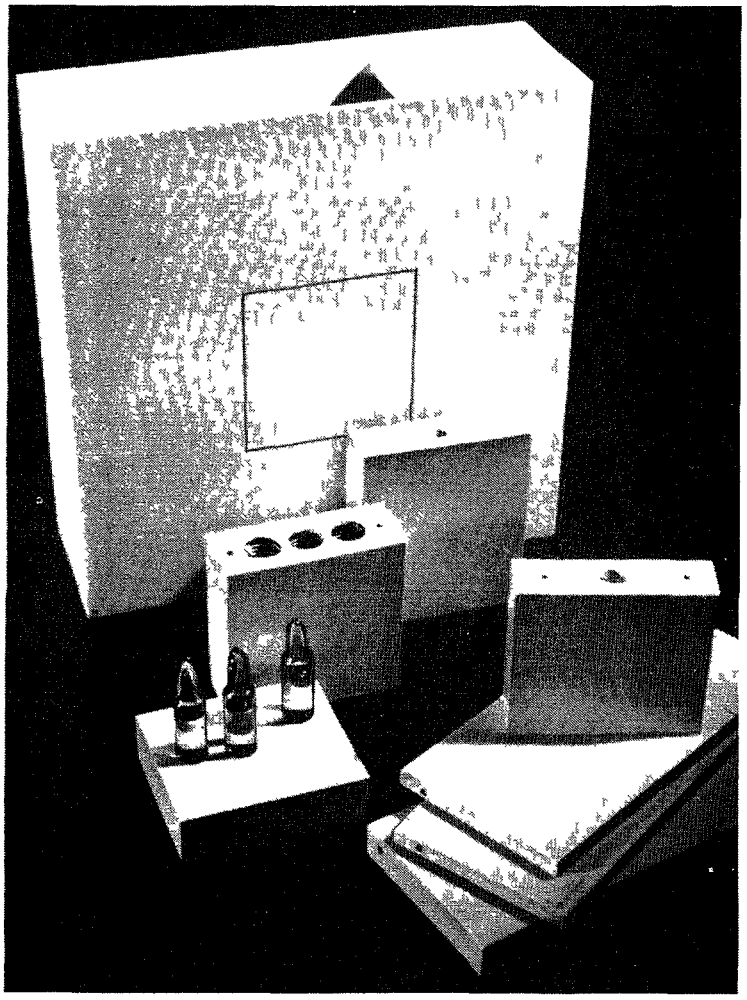
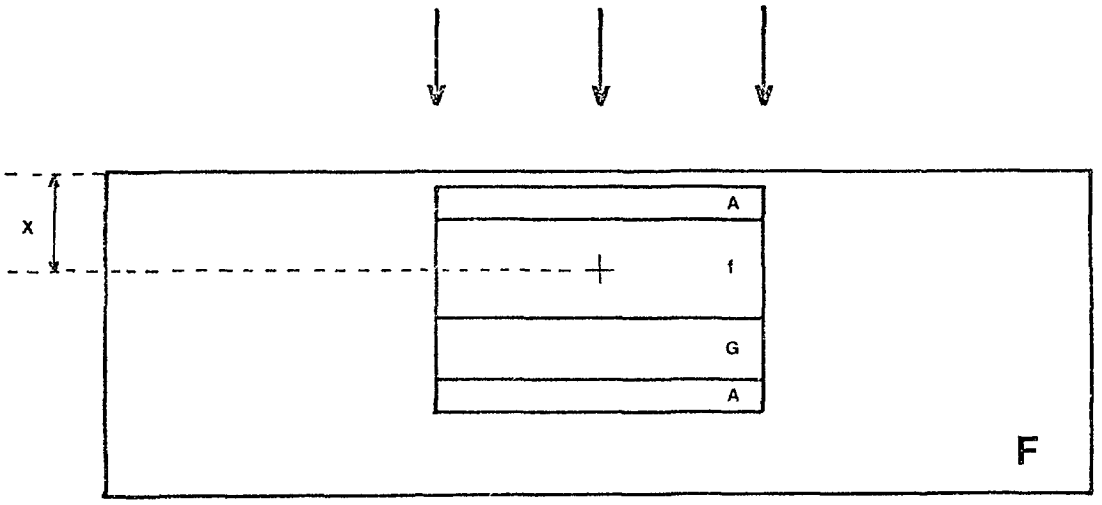


Fig. 2 - View of the transfer dosimeters and of the different elements of the water-equivalent phantom.



	fBAA	AfBA	BfAA	ABfA	AABf
x/cm	2	3	4	5	6

Fig. 3 - Schematic top view of the phantom and orderings of its constituents for obtaining various reference depths x.

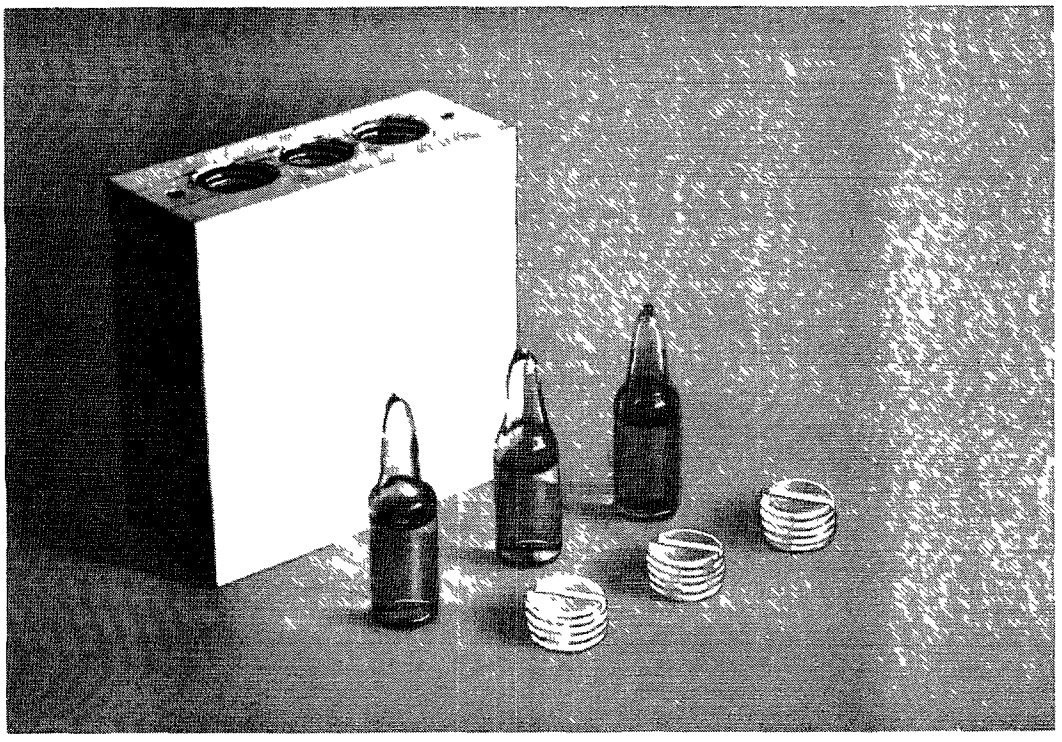


Fig. 4 - View of element "F" containing the three ferrous sulphate dosimeters.

MEASUREMENT ASSURANCE STUDIES OF HIGH-ENERGY ELECTRON AND PHOTON DOSIMETRY IN RADIATION-THERAPY APPLICATIONS

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ABSTRACT

This is a brief review of surveys on the dosimetry of radiation-therapy beams by the National Bureau of Standards (NBS). Covered are the NBS ferrous-sulfate (Fricke) dosimetry service, a recently completed survey carried out with thermoluminescence dosimeters (TLD) on the dosimetry in cobalt-60 teletherapy beams, and plans for a TLD survey of dosimetry in high-energy bremsstrahlung beams.

1. Introduction

At the 1971 IAEA Meeting on National and International Radiation Dose Comparisons,[1] one of the authors (M.E.) discussed in some detail the NBS involvement in what has become known as measurement-assurance studies. At the time, our Fricke-dosimetry service, oriented mainly towards the uniformity of high-energy electron dosimetry in medical therapy, was about three years old. The author discussed its conception, rationale, and mechanics in some detail, and showed some test results. The service is still being performed, in fact the number of participants has increased from around 15 to over 40. Instead of repeating the discussions, which are available in the Proceedings of the 1971 meeting, a brief review is given in Section 2 of this report of some of the technical details of the NBS operation that were not discussed in the earlier report. Also, a progress report on the performance of the participants is given and plans for improvements in procedure are discussed.

At the 1971 meeting, a possible future survey of dosimetry of cobalt-60 teletherapy sources, to be done with thermoluminescence dosimeters (TLD), was also mentioned. Since then, we have completed a one-time voluntary study of the dosimetry of over two-thirds of the U.S. cobalt-60 teletherapy sources. At present, we are working on the design and

calibration of a TLD system to be used in the near future by the U.S. Bureau of Radiological Health (BRH) for a survey of the dosimetry of U.S. high-energy bremsstrahlung beams employed in radiation therapy. Since some of the considerations going into the design of survey programs of this type are of interest independent of the TLD system of choice, they are included in Section 3, although the systems are different from that employed by the IAEA.

2. Fricke Dosimetry for the Survey of High-Energy Electron Beam Dosimetry

Dosimeters are provided to users requesting assistance with comparing their absorbed-dose measurements in high-energy electron beams with those of their peers. The dosimeters consist of ferrous sulfate (Fricke) solution in ground-glass stoppered radiation-resistant quartz spectrophotometer cells enclosed in polystyrene holders, as shown in figure 1. The participants irradiate all but one of the furnished dosimeters to between 50 and 80 Gy to water (5000 and 8000 rad) at electron energies between 5 and 50 MeV, employing the irradiation geometry (field size, type and size of phantom, position of dosimeter in the phantom) given in the Protocol for Dosimetry of High-Energy Electrons.[2] After irradiation, the dosimeters are returned to NBS for spectrophotometric evaluation of the ferric-ion concentration in terms of absorbed dose in the phantom, using the value for the radiation-chemical yield given in the Protocol. Inasmuch as the disturbance of the radiation field by the quartz walls of the spectrophotometer cells is ignored (the same value for the radiation-chemical yield being used over a wide range of electron energies) the method cannot be considered to provide the participants with a highly accurate calibration of their system; it simply provides them with an indication of how their dosimetry compares with that of others.

The Fricke-dosimeter solution used by NBS consists of the following conventional ingredients:

0.001 *M* $Fe(NH_4)(SO_4)_2$, dissolved in
0.8 *N* H_2SO_4, well aerated, and
0.001 *N* NaCl.

Because of addition of NaCl to desensitize the system against organic impurities, we recommed its use below an absorbed-dose rate of about 10^3 Gy/s (10^5 rad/s), since NaCl causes an increase in the rate dependence of the radiation-chemical yield.

A simplified reaction mechanism (without the NaCl) is shown below in order to remind the reader of how O_2 enters into the reaction and determines Fe^{+++} yield:[3]

$$Fe^{++} + OH \rightarrow Fe^{+++} + OH^-$$

$$H + O_2 \rightarrow HO_2$$

$$Fe^{++} + HO_2 \rightarrow Fe^{+++} + HO_2^-$$

$$HO_2^- + H^+ \rightarrow H_2O_2$$

$$Fe^{++} + H_2O_2 \rightarrow Fe^{+++} + OH + OH^-$$

A fresh batch of Fricke solution is prepared prior to each shipment and decanted into the individual dosimeter cells. Rather than using glass vials, we find it advantageous to use the stoppered spectrophotometer cells in which the optical density of the solution is eventually measured. The glass vials would be less costly and directly sealable, but the solution would have to be decanted into spectrophotometer cells for readout. We have shipped Fricke solution in the same spectrophotometer cells for the past 12 years, with an attrition of about 20 percent only. During this period, the relative standard deviation of the average readings in these cells of irradiated Fricke solution has increased from about 0.8 percent to a still satisfactory 1.2 percent, probably because of small nicks or scratches in the cell walls. We therefore consider the initial larger investment in spectrophotometer cells to have been worthwhile. The one major disadvantage of using an unsealed system is the necessity of ensuring shipment at low altitudes or in pressurized plane compartments in order to prevent oozing of the liquid and loss of oxygenation.

We initially cleaned all spectrophotometer cells with detergent in an ultrasonic cleaner and from then on kept them filled with Fricke solution. All other glassware was initially cleaned with hot concentrated sulphuric acid and since then has been kept filled either with Fricke solution or with pure distilled water. No plastics are ever in contact with the Fricke solution. We now produce our own organic-free distilled

water, in a permanganate distillation operation.[4] We measure the change in optical density spectrophotometrically at the conventional 304 nm absorption peak of Fe^{+++} and from it determine absorbed dose to water via published values for the radiation-chemical yield of the ferrous-ferric oxydation reaction. The radiation-chemical yield, $G(Fe^{+++})$, is defined as the number of Fe^{+++} ions formed per 100 eV. Expressed in terms of molar concentration, M (mol/l) and absorbed dose D (Gy), this relationship becomes:

$$(1) \qquad G(Fe^{+++}) = 0.942583 \times 10^{7} \, M/D \,,$$

if the mass density of the Fricke solution is taken to be 1.024 g cm^{-3}. Optical (transmission) density is measured at 304 nm. Transmission density corrected for losses through scattering in the optics of the spectrophotometer is usually called absorbance, A, which by Beer's law is related to the molar concentration, M, by

$$(2) \qquad A = \varepsilon \, M \, d,$$

where d is the path length through the solution, in centimeters, M is the molar concentration in moles per liter and ε is the molar extinction coefficient. If one combines equations (1) and (2) one obtains

$$(3) \qquad D = 0.042583 \times 10^{7} \, \frac{\Delta A}{\Delta\varepsilon \, G(Fe^{+++}) \, d}$$

where ΔA is the change in absorbance before and after irradiation of the solution, and $\Delta\varepsilon \sim \varepsilon(Fe^{+++})$.

We initially chose to do our spectrophotometry at the conventional wavelength of 304 nm but may in the future decide to switch to a readout at 224 nm.[5] The advantages of spectrophotometry at 224 nm are (a) an extension of the useful absorbed-dose range (about 5 to 350 Gy) to doses lower by a factor of about 2; and (b) a smaller dependence of the molar extinction coefficient, $\varepsilon(Fe^{+++})$, on temperature (0.13% per °C). Prior to switching to readout at 224 nm, we would verify that, at this wavelength, the extinction coefficient of Fe^{++} is neglibly small compared to that of Fe^{+++}, as it is at 304 nm and that, as a consequence, $\Delta\varepsilon$ in equation (3) still can be set equal to $\varepsilon(Fe^{+++})$.

For spectrophotometry to yield sufficiently accurate results, the following parameters have to be checked:

(a) Wave-length and absorbance scales. NBS provides for this purpose standard reference filters or liquids in quartz cells.[6] Since aqueous potassium nitrate has an absorption peak at ∿ 304 nm, it may be used for day-to-day checks on wavelength stability and absorbance-scale linearity.

(b) Molar extinction coefficient, $\varepsilon(Fe^{+++})$. While values for this quantity are given in textbooks, it is advantageous to determine it experimentally for one's own instrument and operating conditions, particularly because of its relatively strong temperature dependence and also because of the possible deficiencies in the optics which, in some instruments, cause its value to change with absorbance level. This determination involves the careful preparation of Fe^{+++} solutions of a number of different known molar concentrations, starting with electronically purified iron.[7] In the NBS Fricke-dosimetry service, absolute dose determinations of high accuracy are not attempted; therefore, an absolute determination of the molar extinction coefficient actually is not required; yet, it still is necessary for us to determine whether the extinction coefficient is constant over the absorbance range of interest.

One of the main features of our procedure is that we pre-irradiate all dosimeters, giving about 50 Gy (5000 rad) of cobalt-60 gamma radiation and using only dosimeters whose performance proves satisfactory.[8] Inasmuch as there is absorbance growth with time after preparation even in the dosimeters with satisfactory performance, ΔA in equation (3) has to be corrected for growth between preparation and readout, particularly since, because of delays in dosimeter returns from some of the participants, the time between initial and final readout if of the order of six weeks. For this correction, we use the average growth on all unirradiated controls (shipped and unshipped) which we find adds at least 1 percent to the total uncertainty of our procedure because growth is different for different cells.

The overall uncertainty in our dose determinations currently is taken to be about 4 percent, which could be decreased readily by the use of more than one dosimeter per measurement point and by a more uniform growth in absorbance from cell to cell between the readouts before and after irradiation by the participants, as might be achievable in a controlled

sealing process of the type discussed in the next paragraph. The quoted uncertainty does not include the systematic uncertainty caused by the assumption of a constant G value over the electron-energy range from 5 to 50 MeV unaffected by the presence of the quartz cells, or caused by non-uniformity in the absorbed dose over the 1-cm depth of the dosimeters' sensitive volume.

Over the years, we have come to regret that we started with an unsealed system in spite of its operational advantages, since a sealed system may offer better stability. For this reason, we are now investigating the use of sealable spectrophotometer cells with necks graded from quartz to Pyrex glass, filled with Fricke solution and sealed. If it were possible to produce a batch of such dosimeters that is relatively stable and of uniform sensitivity, one could use it for many successive irradiations and dose evaluations, particularly in conjunction with an up-to-date stable and sensitive spectrophotometer and readout at a wavelength of 224 nm, which might make it possible to go to lower doses and nevertheless decrease measurement uncertainty.

We also have been discouraged by the relatively small improvement in the overall performance of the participants: If we consider all the results obtained in the years from 1967 to 1975, we find that over 40 percent of the doses assigned by the participants differed from the NBS dose interpretation by more than 5 percent. These results are shown in figure 2. The improvement, if any, among regular participants was small, at least up to 1975. However, during the last year or two, considerable overall improvement was observed. In the last survey, the dose assignment of only 16 (or 24 percent) of the 68 dosimeters irradiated differed from the NBS dose interpretation by more than 5 percent. This is an encouraging sign of an increased awareness by the radiation-therapy community of the importance of careful dosimetry. We hope that we are contributing at least to a small extent to this awareness.

3. TLD Systems for Nationwide Surveys of Cobalt-60 Teletherapy and High-Energy Bremsstrahlung Dosimetry

3.1 Cobalt-60 Teletherapy-Dosimetry Survey

The cobalt-60 teletherapy survey was a one-time endeavor supported in part by the U.S. Bureau of Radiological Health (BRH). We mailed TL

dosimeters to all U.S. users of teletherapy sources who had expressed their willingness to participate. Figure 3 shows the commercially available hermetically sealed dosimeter bulb containing a heater strip and small plaques of the CaF_2:Mn TLD material, which for shipment was enclosed in a suitable plastic container. While this system is initially more expensive than TLD powder or bare plaques ("chips") of the TLD material, it can be handled by a technician with no previous experience in thermoluminescence dosimetry. Also, since no large variations in source spectra were expected in the teletherapy survey, it was decided to use the CaF_2:Mn phosphor which in the past we had found to perform reliably and which often cannot be used because its atomic number is higher than that of water and tissue. The readout system consisted of a commercial unit containing the heater-photomultiplier assembly, while general laboratory equipment was used for timing, and for integrating, digitizing and recording the signal. With dose interpretation from the average of the readings on 5 dosimeters, an overall uncertainty of about 2.5 percent was attained. This includes the uncertainty introduced by the need for correcting for a trend in the readout system, which tended to become more efficient with consecutive readouts of one dosimeter every 25 or 30 seconds over a period of several hours. (The effect probably was due to a rise in the temperature of the reader electronics which was not entirely compensated for by the photomultiplier cooling circuit.) The results of the survey are shown in Figure 4, demonstrating that for over 80 percent of a total of about 900 units surveyed the dose interpretation was within 5 percent of the requested dose of 3 Gy (300 rad) to water.

3. High-energy Bremsstrahlung-Dosimetry Survey

In the survey of high-energy bremsstrahlung dosimetry, one cannot rule out that the contribution to dosimeter response of low-energy photons might vary sufficiently from machine to machine to make the use of the high-atomic-number CaF_2:Mn dosimeter undesirable. Because of our experience in the past with spurious readings on LiF both in the form of powder and in the form of TLD-100 chips we first investigated the state of the art of TL dosimetry with lithium borate, which is commercially available either in the form of discs in which the crystalline powder is incorporated in a vitreous

material(Studsvik) or in the form of pressed-powder chips (Harshaw).* The results revealed that in view of the present state of development of lithium-borate TLD, the material could not be recommended for the planned survey. (The lithium-borate powder in the vitreous matrix fades more than the pressed lithium-borate chips, but in contrast to the pressed chips it is not hygroscopic.**) We therefore advised BRH to continue the use of LiF TLD-100 which they are employing for a number of other surveys, in conjunction with a hot-nitrogen reader. In a preliminary study of the behavior of 200 identically irradiated TLD-100 chips handled with suction pickup and reproducibly annealed for 1 hour at 400 °C followed by 1 hour at 100 °C before irradiation and another 10 minutes at 100 °C before readout, spurious readings did not occur. This annealing and readout procedure was repeated nine times over the course of two weeks. The results of the study indicate that there is about a 1.2-percent relative standard deviation from the average of the day-to-day readings on a single chip. The relative standard deviation from the average of the readings of all the chips in the batch generally will be larger, its value depending on the spread in the readings of the selected chips after identical exposure. For the present study, a batch of 100 chips was selected with a $\pm$ 3 percent spread in readings. On any given day, this batch yielded a 1.8-percent relative standard deviation from the average of the readings of all the chips.

So far, our investigations have included studies on the choice of phantom material and phantom size for source-to-axis-distance (SAD) irradiations with a 10 cm x 10 cm field size at the various depths of interest, and on the possibility of obtaining depth-dose information on the participants' beam by a single irradiation of a number of dosimeters positioned at different phantom depths, all on the beam axis. The results were:

(a) Within the measurement uncertainty, the TLD readings obtained over a range of depths in the phantom from about 0.5 to 10 g cm^{-2}

*Commercial product identification does not imply a recommendation or endorsement by NBS, nor does it imply that NBS considers the identified products to be the best available for the purpose.

**We subsequently learned that the increase in fading also will be observed on the crystalline powder used by Harshaw when it is introduced in a vitreous matrix.

with cobalt-60 gamma radiation are nearly the same in phantom consisting of a polymethyl methacrylate (PMMA) cube with 15-cm sides and one with 20-cm sides. However, there is a trend toward higher readings in the larger phantom.*

(b) Within the measurement uncertainty, the readings obtained in a PMMA phantom in one single irradiation with dosimeters at depths between about 0.5 and 10 g cm^{-2} are the same as those obtained in separate measurements at each depth. However, in a water phantom in which the dosimeters are held in plastic inserts, there is a significant difference in the readings of dosimeters irradiated separately and simultaneously, probably because of displacement of water by the plastic inserts.

We further obtained a cobalt-60 gamma-ray calibration of the TLD-100 samples in PMMA in terms of absorbed dose to water as a function of depth in the phantom. The distance between the source and the detector was kept constant (1 m) and the beam cross section at this distance was 10 cm x 10 cm. The readings obtained were compared with source-standardization data derived from absorbed-dose calorimetry in the same beam for the same field size and distance. Figure 5 shows the results. The readings were arbitrarily fitted to the absorbed-dose curve at a depth of 5 cm, but could be fitted just as well at any other depth. Also, in order to tie in directly with IAEA measurements, we sent our phantom of 20-cm side length, loaded in several depths with individually calibrated LiF-TLD-100 samples, to Massachusetts General Hospital (MGH) for irradiation in their 10-MV bremsstrahlung beam under the conditions employed in the cooperative study with the Harvard School of Medicine and the IAEA. A preliminiary evaluation of the results after return of the loaded phantom to NBS gave a value of 1.011 for the quotient of the absorbed dose to water quoted by MGH and the cobalt-60 equivalent dose to water evaluated at NBS with the aid of absorbed-dose calorimetry data. This agrees well within the uncertainties of the measurement and evaluation with the value of 1.014 for this quotient, obtained in the MGH-IAEA experiment of March 1, 1979. (See table II on page 124 of these Proceedings.) For the NBS-MGH study, the relative standard deviation of

*This finding agrees with earlier depth-dose measurements with ion chambers in graphite phantoms made by J. Pruitt and S. Domen of our laboratory, who found a difference of 0.7 percent at a 10-cm depth.

a single reading from the average of nine TLD-100 sample readings in each of four different phantom depths was about 0.7 percent.

Finally, in order to arrive at the number of dosimeters required per measurement (corresponding to the number of readings from TLD powder at any one measurement position) for a preselected level of uncertainty, we made a careful assessment of the random and systematic uncertainties entering into each step of the dose interpretation. The steps considered were:

(a) Cobalt-60 irradiation of n dosimeters (applicable also to powder sufficient for n readings) in the selected geometry, and readout.

(b) Relating the average of the n readings to the cobalt-60 gamma-ray exposure at the point.

(c) Irradiation of sets of m dosimeters in various calibrated high-energy bremsstrahlung beams of the type to be surveyed.

(d) Relating the average of the m readings to absorbed dose to water in the high-energy bremsstrahlung beam at the depth of interest.

(e) Determination of the correction factor to the readings obtained with cobalt-60 gamma rays (step a) if samples are to be irradiated with high-energy bremsstrahlung instead (step c).

Preliminary results of our analysis show that, for suitably selected batch-calibrated TLD-100 samples, averages from readings on 9 samples lead to an uncertainty of 3 to 4 percent in the final dose interpretation. When individually calibrated samples are used, this value is lower by about one percent.

At present, the absorbed dose for high-energy bremsstrahlung is usually determined from the response in the bremsstrahlung beam of an ionization chamber originally calibrated in terms of exposure with cobalt-60 gamma radiation and multiplied by a suitable correction factor (C_λ). Inasmuch as the uncertainty in C_λ, which may be of the order of 4 to 5 percent, will be the same for all participants, it was decided to exclude it from the estimate. If, at a later date, calorimetric measurements will be used to obtain the absorbed dose for the high-energy bremsstrahlung irradiations, the treatment of the resulting uncertainty will be reconsidered.

Acknowledgment. The work related to dosimetry in cobalt-60 teletherapy beams discussed in this paper was supported in part by the Radioactive Materials Branch, and the work related to dosimetry in high-energy bremsstrahlung beams by the Medical Physics Branch of the Bureau of Radiological Health, Food and Drug Administration, U. S. Department of Health, Education and Welfare.

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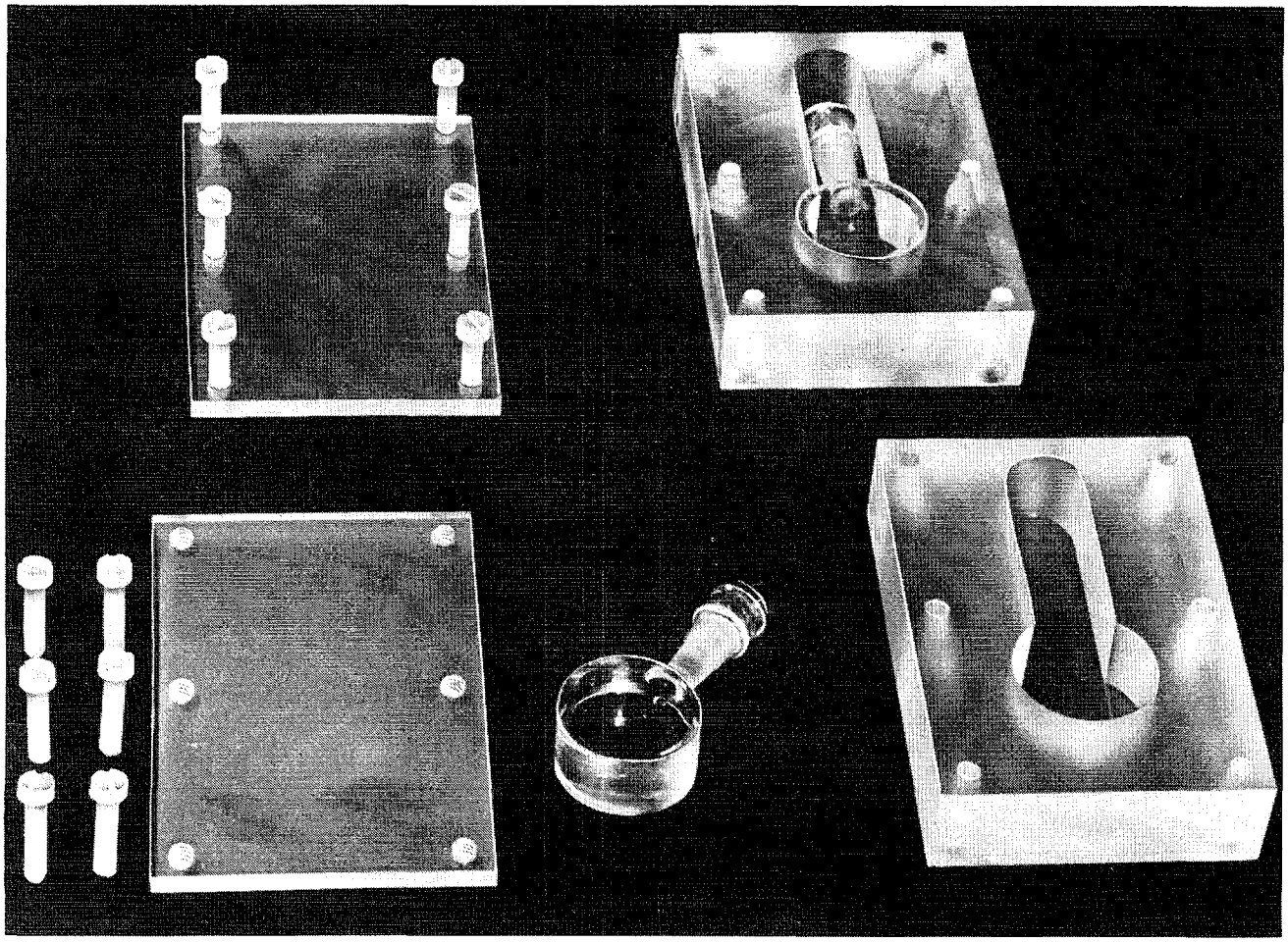

Fig. 1 Fricke Dosimeter Units. The spectrophotometer cell fits snugly into the polystyrene block; in the finished assembly, a styrofoam plug presses against the stopper, and keeps it in place.

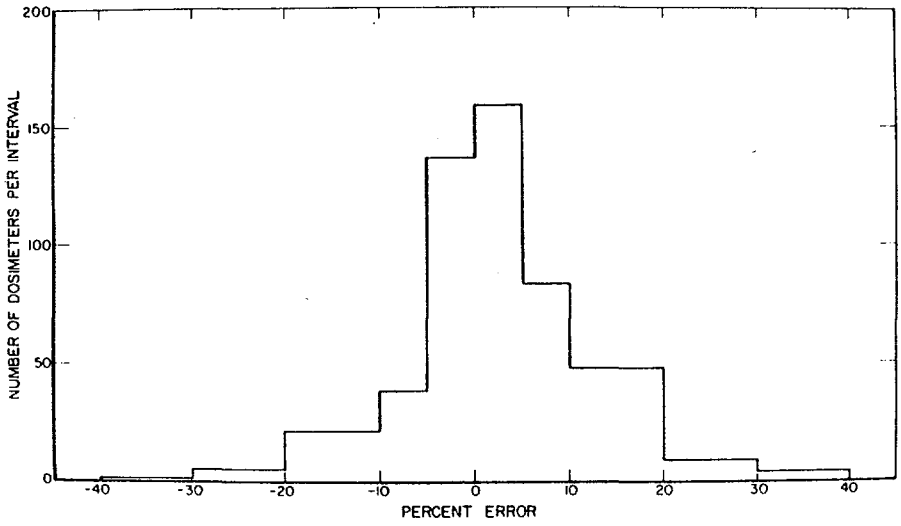

Fig. 2 Electron Dosimetry Performance, 1967 through 1975. The doses assigned to 58 percent of the dosimeters agreed with the NBS dose interpretation to within 5 percent; 23 percent of the dosimeters showed differences between 5 percent and 10 percent, and 19 percent differed by between 10 percent and 40 percent.

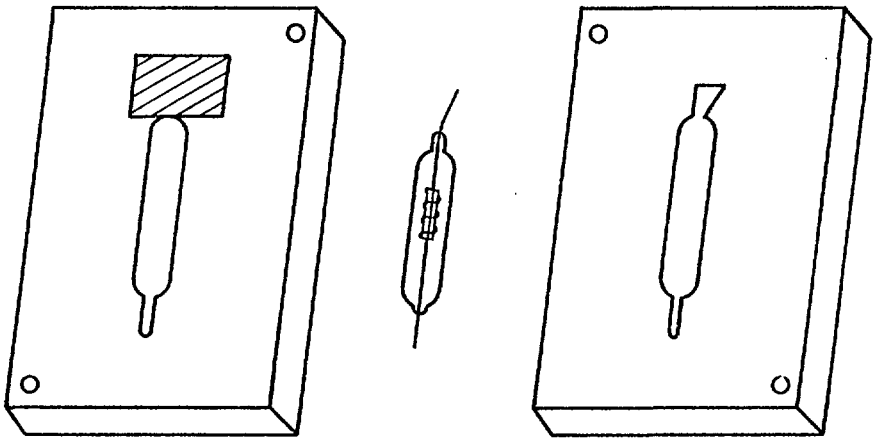

Fig. 3 Schematic Diagram of the CaF_2:Mn Bulb Dosimeter (center) and the Two Halves of the Polystyrene Holder (left and right).

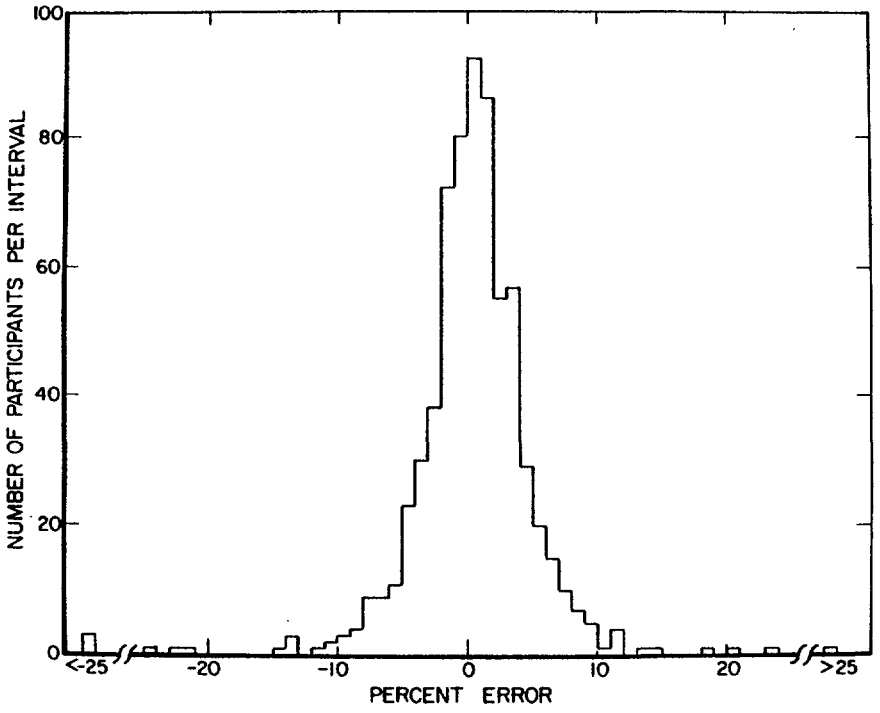

Fig. 4 Performance of Participants Involved in the Survey. Shown is the difference, in percent, between the dose to be delivered by the participants and the NBS dose interpretation from the average of the responses of the five irradiated dosimeters.

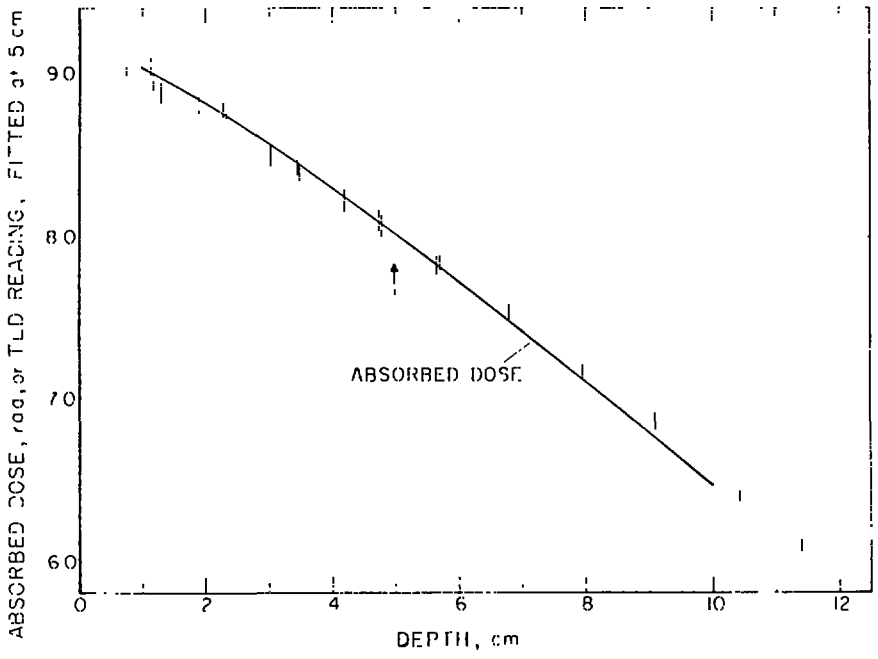

Fig. 5 ^{60}Co Calibration of TLD-100 in a 15-cm x 15-cm x 15-cm Polymethyl Methacrylate (PMMA) Phantom. 10-cm x 10-cm field size at each depth. Solid line: absorbed dose to water; error bars: standard deviation (~ 0.7) for a single dosimeter reading obtained from the average reading of 9 calibrated dosimeters at each depth. The average dosimeter data were fitted to the absorbed-dose curve at the arrow (at a depth of 5.00 cm in PMMA, corresponding to 5.77 g cm^{-2} in water, which is the depth in water for which the percent depth dose is approximately the same as at 5.00 cm in PMMA).

A REVIEW OF THE RESULTS OBTAINED BY THE NPL/PTB FRICKE DOSEMETER CALIBRATION SERVICE IN GERMAN RADIOLOGICAL CENTRES

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In 1972 the Physikalisch-Technische Bundesanstalt (PTB), the national standardizing laboratory in the Federal Republic of Germany, decided to make the Fricke Dosemeter Calibration Service of the British National Physical Laboratory (NPL) available to German radiological centres. This service has been established by Ellis in 1969 (1). The main features of this postal reference service are as follows: Fricke solution in sealed pharmaceutical glass ampoules is made available by the NPL twice per year in May and November. The PTB distributes the dosemeters to the participating institutions, collects them after the irradiations, and returns them to the NPL for evaluation. A water phantom and data sheets to protocol details of the irradiation conditions are provided by the PTB. Moreover, the PTB offers general advice and assistance in analyzing the results. Apparently this activity is very similar to the manner in which intercomparisons are carried out by the IAEA. Each participant of a dosemeter issue can obtain a set of 10, 12 or 14 ampoules, 4 of which have to be left unirradiated as controls. Of course exceptions are possible and higher numbers of ampoules are conceded when an extensive calibration program is taking place in any center. The period of time that elapses between dispatching the dosemeters from the NPL and the evaluation is 5 weeks on an average.

The dosemeters are offered for irradiations in the water phantom with cobalt-60, high energy electrons (> 8 MeV), and megavoltage photons. The participants are asked to irradiate at depths and apply conversion factors given by the corresponding ICRU Reports 14, 21 and 23. In order to secure identical irradiation conditions in each institution, the phantoms are supplied by the PTB. The user may either buy or rent the water phantom. The water containers themselves are ordinary polystyrene fish tanks (Fig. 1) which are kept in stock. A suitable lid, a holder for the chemical dosemeter, and fitted holders for the ionization chambers, according to specifications given by the user, are manufactured in the PTB workshop.

With cobalt sources the irradiations of the Fricke dosemeters and the dosemeters to be calibrated are usually performed sequentially on the beam axis in the phantom. For irradiations with accelerators it is recommended to irradiate both dosemeters simultaneously on both sides of the beam axis and to swop them several times during the irradiation in order to overcome beam instabilities.

Each dosemeter should obtain an absorbed dose of about 40 Gy. For this case a random uncertainty of about ±0.5 % is quoted by the NPL for cobalt irradiated ampoules at the 95 % confidence level with 8 degrees of freedom. To determine this uncertainty, a set of ampoules of the same batch is irradiated with cobalt in the NPL at about the same time as the irradiations take place in the centers. These ampoules are evaluated together with the returned dosemeters of the participants. Since 1977, further independent cobalt irradiations have been carried out in the PTB in order to rule out "travel effects". The differences resulting from the absorbed dose determinations by the PTB and the NPL have always been less than 0.5 %.

After a pilot study in November 1972 the regular Fricke dosemeter service for German hospitals and other interested irradiation centres started in May 1973. The table illustrates the development till now.

Table. Number of participating centres and of dosemeters irradiated in Germany between 1973 and 1978.

Date of issue	Number of centres	Dosemeters irradiated with		
		Co	electrons	photons
May 1973	9	41	19	10
November 1973	6	7	33	11
May 1974	9	25	40	16
November 1974	4	7	18	8
May 1975	7	23	21	13
November 1975	8	25	28	24
May 1976	7	25	26	10
November 1976	11	35	23	34
May 1977	7	26	27	12
November 1977	11	31	31	8
May 1978	9	25	27	18
November 1978	9	28	31	20
Total	97*	298	324	184

* 40 different centres. Some of them took part several times.

Fig. 2 shows frequency distributions of the ratio of absorbed dose determined by the user to absorbed dose measured by means of the Fricke dosemeters for cobalt 60, electrons, and megavoltage photons. Additionally the frequency distribution of the cobalt irradiated dosemeters (left side below) is split into two fractions. Intercomparisons made during the first period from May 1973 to May 1976 (left side above) and those during the second period from November 1976 to November 1978 (left side middle). The most striking feature of these distributions is the asymetric shape. Whereas the asymetry is only slightly indicated during the initial period, it is more marked during the later one. This may be explained as follows: In the beginning the users could not refer to reliable calibration factors of their ionization dosemeters. Hence the distribution is wide-spread. Later on some users adopted the calibration factor obtained

from a previous participation in the Fricke calibration service. Other institutions used calibration factors obtained from the manufacturer, the Physikalisch-Technische Werkstätten Freiburg (PTW). There are, however, some indications that the calibration factors that originate from this laboratory tend to be lower by 1.5 % than those originating from the NPL. The difference may eventually be due to the primary standardizing laboratory which is the PTB. Therefore the PTB is going now to investigate this phenomenon carefully.

The fact that it is possible to resolve such small effects, proves the precision claimed for measurements with Fricke dosemeters. This is an essential advantage of the Fricke dosimetry, which should be taken into consideration for intercomparisons, when a total uncertainty of less than 2 % is required.

The results of the electron irradiations are poorer. Several facts increase the uncertainty of electron intercomparisons, for instance:

a) Strong dependence of the absorbed dose conversion factors on the electron energy at the effective point of measurement which is usually different for the ionization chamber and the Fricke dosemeter.
b) Unknown contamination of the primary electron beam by photons or stray electrons.

Furthermore one has to realize that most of the chambers have not been designed for electron irradiations and might have suffered from a "polarity effect" (2). It should also be mentioned that the most significant discrepancies occured when the electron energy was below the recommended lower limit of 8 MeV. Allowing for all these sources of uncertainty, the results are quite satisfying.

Similar considerations are valid for the megavoltage photon irradiations. Of course the asymetric structure of the cobalt distribution is also reflected by the electron and photon distributions since many institutions carried out intercomparisons using the same calibrated ionization chamber for all three types of radiation.

Finally two outstanding results of this calibration service are to be mentioned. The first result is that a discrepancy between absorbed dose determinations based on the C_λ concept and on the measurements with Fricke solution respectively has been found for 42 MeV bremsstrahlung already in 1973 (3). On an average, the absorbed dose determinations by means of Fricke solution usually give values that are about 3 % higher than the results of ionization chamber measurements for this radiation quality. This might arise from a true value of the absorbed dose conversion factor that is higher than the value recommended by the ICRU. In 1974, a discussion on the discrepancy between the C_E and the C_λ concept was launched, mainly by Greening (4). Now it is commonly agreed that the composition of the ionization chamber wall affects the conversion factor

and increases the recommended value by 3 % for 42 MeV bremsstrahlung, if an ionization chamber with air equivalent walls is used (5). Investigations at the PTB confirmed these findings (6).

The second outstanding result is an event in a German university hospital. It happened soon after the exchange of the source in a cobalt unit. In spite of a recalibration of the ionization dosemeter before the exchange procedure and in spite of regular checks of the dose rate, the measurements with Fricke dosemeters disclosed a 10 % deviation from the dose rate assured by the hospital. Another recalibration of the ionization chamber was carried out by PTB. Surprisingly this recalibration completely confirmed the results obtained by the Fricke dosemeters. It has to be admitted that the whole affair is still rather mysterious. Anyway the Fricke calibration service has prevented that serious harm was caused.

The author gratefully acknowledges many useful discussions with Dr. S. C. Ellis of the National Physical Laboratory Teddington.

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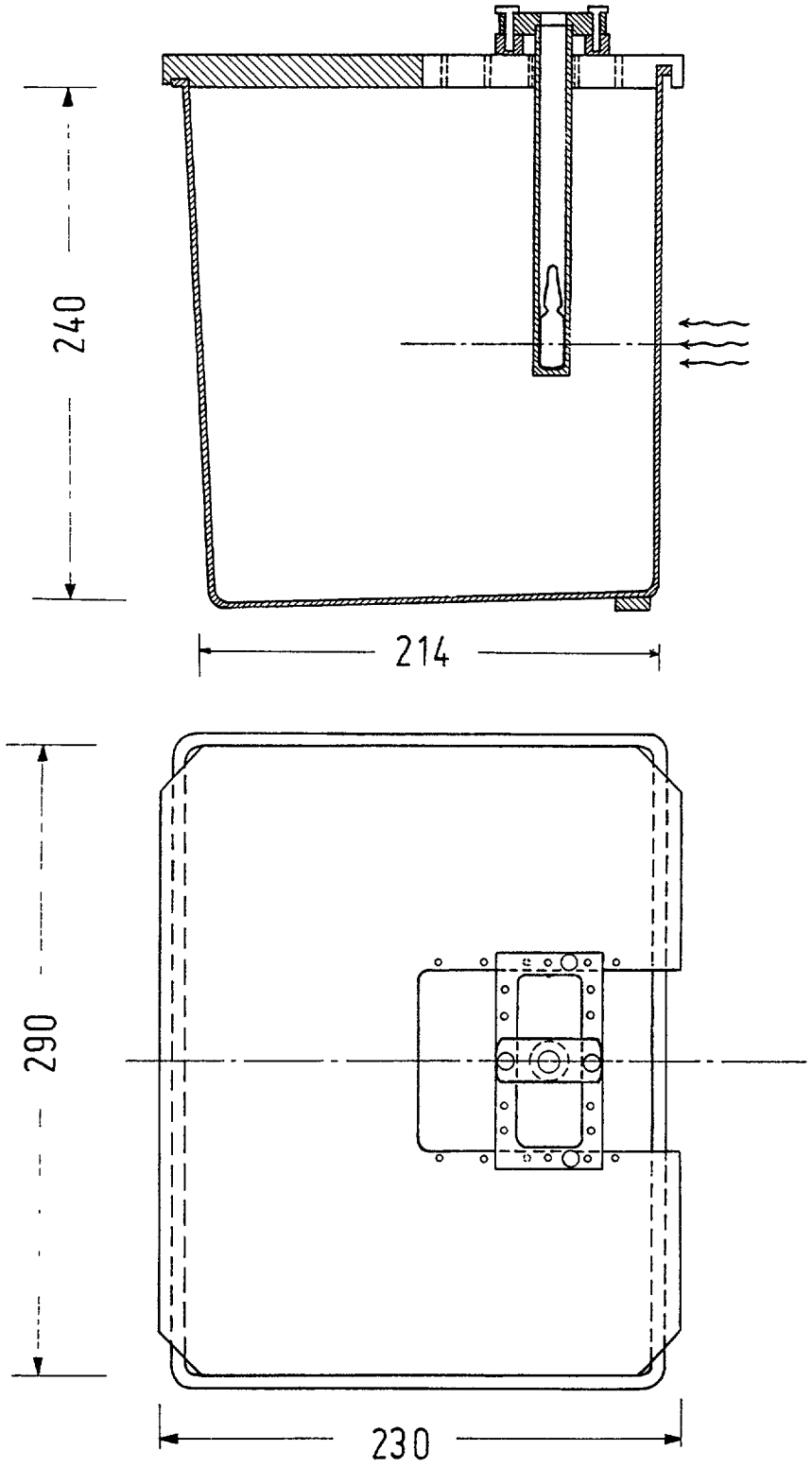

Fig. 1. Sketch of the polystyrene water phantom with holder for a chemical dosemeter.

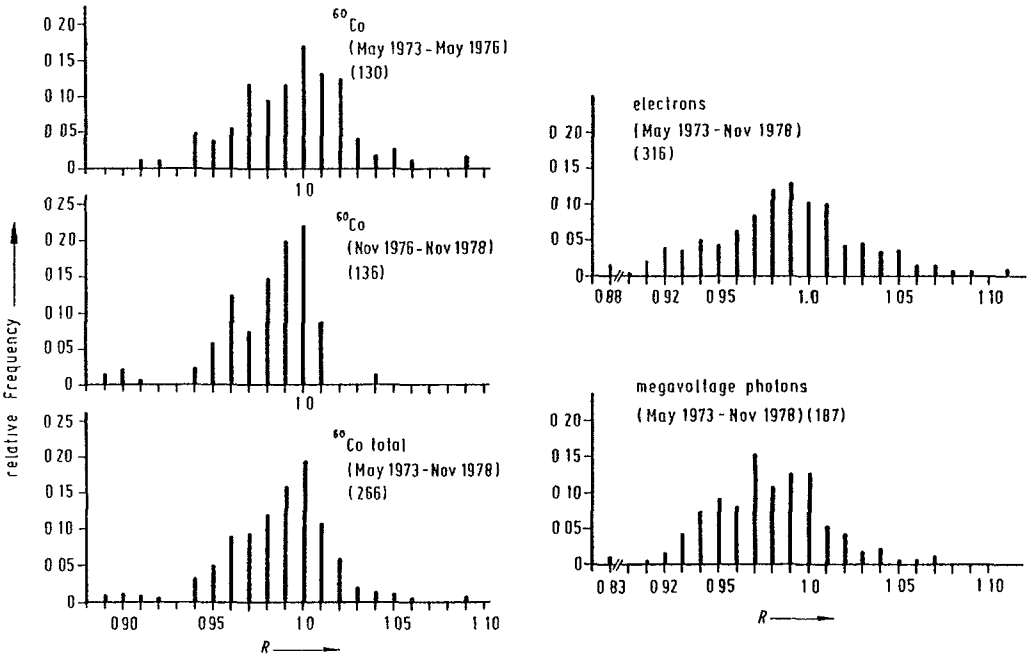

Fig. 2. Frequency distributions of the ratio R of absorbed dose determined by institutions to absorbed dose measured by NPL Fricke dosemeters for various radiation qualities. In brackets time period and number of ampoules.

THE USE OF $FeSO_4$ IN SOME PRACTICAL ASPECTS OF HIGH-ENERGY PHOTON AND ELECTRON DOSIMETRY

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Abstract

The use of $FeSO_4$ in some practical aspects of high-energy photon and electron dosimetry.

The advantages of $FeSO_4$ are discussed with respect to its applications in practical high-energy photon and electron dosimetry: (1) the calibration of ionization chambers, (2) the evaluation of the importance of ion recombination in chambers exposed to high dose-rates, (3) the determination of absorbed dose in radiobiological samples and (4) the use of $FeSO_4$ as a transfer dosemeter.

The absorbed dose conversion factors, C_E or C_λ of an ionization chamber can be determined by comparison with $FeSO_4$. The response of the $FeSO_4$ dose meter (or the G-value) as a function of the beam quality can be considered as constant for high-energy photons and electrons in the usual energy range. An $FeSO_4$ dose meter can also be used to evaluate the importance of ion recombination in a chamber exposed to high dose-rates of electrons, since its response is independent of dose-rate (up to 2×10^6 Gy.s^{-1}).

Examples are given to illustrate the interest of $FeSO_4$ for measurements of absorbed dose in biological samples, mainly in depth in electron beams where the dose gradient is high. $FeSO_4$ can be assumed to be insensitive to energy variation in depth (or to dose-rate variation); it does not introduce any heterogeneity and no displacement factor has to be applied; finally, the dose meter solution can occupy a volume identical to that of the biological systems to be irradiated. For these applications, the results obtained with $FeSO_4$ are compared with those obtained with other dosimetric systems. Our experience with $FeSO_4$ used as a transfer dosemeter for inter-comparisons between centers is reported.

INTRODUCTION

Although ionization chambers are the dosemeters most commonly used for high-energy photon and electron dosimetry, the $FeSO_4$ chemical dose meter has properties which make it particularly suitable for several applications. The purpose of this paper is to report the main points of our experience with the Fricke dosemeter in practical dosimetry of high-energy photon and electron beams.

The main advantages of the $FeSO_4$ dose meter can be summarized as follows (Ref. 1 , 2 , 3):

(1) A high degree of reproducibility (1%).For all the applications considered in this paper we shall rely only upon the reproducibility of the $FeSO_4$, and not upon its accuracy.

(2) No (or negligible) variation of the "response" of the $FeSO_4$ dose meter (optical density/ unit of absorbed dose or G-value) as a function of the radiation quality in the range of high-energy electrons - and photons - up to about 40 MeV.

(3) The response of the $FeSO_4$ dose meter (or G-value) is independent of the dose-rate up to 2×10^6 Gy. s^{-1}.

(4) No (or negligible) heterogeneity is introduced by the detector (and its container) in the irradiated medium.As a consequence, under usual conditions, there is no (or negligible) modification of the electron flux introduced by the detector.

(5) The dose meter solution can be irradiated in thin layers (a few millimeters) or, for radiobiological experiments, the $FeSO_4$ solution can occupy different volumes and, in particular, volumes identical to those occupied by the biological systems to be irradiated.

The disadvantages of the $FeSO_4$ dose meter are also well known. They are mainly:

(1) Low radiosensitivity : doses of about 100 Gy (or at least 50 Gy) are needed for precise measurements;

(2) The $FeSO_4$ solution has to be prepared and handled very carefully and kept in perfectly clean containers.

Taking into account these general properties of $FeSO_4$, its interest in practical dosimetry of high-energy photons and electrons will be considered with respect to four applications :

(1) The calibration of ionization chambers;

(2) The evaluation of the importance of ion recombination in ionization chambers exposed to high dose-rates of electrons;

(3) The use of $FeSO_4$ for determination of absorbed dose in radiobiological samples;

(4) The use of $FeSO_4$ as a transfer dosemeter.

1.CALIBRATION OF IONIZATION CHAMBERS FOR HIGH-ENERGY PHOTONS AND ELECTRONS BY COMPARISON WITH $FeSO_4$

The measuring instrument commonly used as a local standard in a radiotherapy department is still an ionization chamber.For ^{60}Co (or 2 MV x-rays),calibration of an ionization dose meter can be obtained from - or checked by - standard laboratories in terms of exposure

(röntgen) or absorbed dose (gray). In France, such facilities exist at the L.M.R.I. (Laboratoire de Mesure des Rayonnements Ionisants) at Saclay (Ref.4).

However, for high-energy photons and electrons, calibration facilities are not yet easily available. For these conditions, direct comparison with the $FeSO_4$ dosemeter provides an acceptable solution for calibration of the reference chamber in a radiotherapy department. This has been the method used in our Center for many years (Ref. 5 , 6).

As the chamber has been calibrated for ^{60}Co, calibration for high-energy photons and electrons is obtained by comparing, in ^{60}Co, photon and electron beams, the readings of the chamber and of the $FeSO_4$ dosemeter. We have checked that the $FeSO_4$ dosemeter does not introduce any heterogeneity and we assume that its response is independent of beam quality (Ref 2 , 7).

This has been measured recently in very careful sets of experiments carried out by COTTENS (Ref. 3) for electron energies ranging from 3.5 to 14.5 MeV. A G-value of $1.604 \pm 0.035 \cdot 10^{-6}$ mol $\cdot kg^{-1} \cdot Gy^{-1}$ was found for 7 to 14.5 MeV electrons and a G-value of $1.597 \cdot 10^{-6}$ mol.$kg^{-1} \cdot Gy^{-1}$ for 3.5 MeV electrons. Moreover a survey of the G-values obtained from calorimetric measurements has been published by SVENSSON and BRAHME (Ref.8). This survey indicated that the difference between the G-values could be partly related to inaccuracies in ε determinations and a mean G-value of $1.607 \pm 0.017 \cdot 10^{-6}$ mol.kg^{-1}.Gy^{-1} was calculated.

As already mentioned we use $FeSO_4$ only for relative measurements in the applications considered in this paper. $FeSO_4$ can easily be calibrated by measuring its "response" (optical density, 25°C, 304mμ) to given doses of gamma-rays. Absolute calibration of each part of the Fricke dosemeter system (spectrophometer, solution) would normally require long and difficult experiments.

Calibration obtained with this method is valid even if the beam energy is not known with great accuracy.

When an ionization chamber dose meter is exposed to high-energy electrons, the absorbed dose in a water phantom may be expressed by the formula (Ref. 2)

$$D_W = M.N_c.C_E \quad (1)$$

where:

D_w = absorbed dose (in Gy) in water at the point of measurement when the chamber system is replaced by water.

M = instrument reading corrected for temperature, pressure and humidity.

N_c = exposure calibration factor of the chamber dosemeter for ^{60}Co gamma-rays.

C_E = overall conversion factor to absorbed dose in water.

C_E includes:

-a correction factor for attenuation of photons in the chamber wall for ^{60}Co radiation during exposure calibration which is assumed to be 0.985 (Ref.9);

- the ratio of mass stopping powers for water and air, which is valid for the mean energy of the primary electrons at the point of measurement;

- the perturbation correction factor.

C_E values have been recommended (Ref.2) for different initial electron energies and different depths in water.

Similary, for high-energy photons, and in particular for the reference radiation quality (^{60}Co), the absorbed dose at the point of measurement in a water phantom may be expressed by (Ref.1)

$$D_W = M.N_c.C_\lambda \quad (2)$$

where:

D_w, M and N_c have the same meaning as in Eq. (1)

C_λ = overall conversation factor to absorbed dose in water (in Gy/R).

The recommended value of C_λ for ^{60}Co is 0.95 (Ref.1)

Measured C_E values for a Nuclear Enterprises chamber are presented in Table I and compared with the C_E values recommended by ICRU (Ref.2) and derived from the calculated data of BERGER and SELTZER (Ref.10) and KESSARIS (Ref.11). The irradiation techniques as well as the chemical methods have already been published (Ref.6 ,12). A close agreement is reached for the conditions which have been studied: electron beams from 10 to 33 MeV (incident energy) produced by three different types of generators. The statistical errors in the measurements (confidence level of 95%) are indicated in the Table. A set of six Nuclear Enterprises chambers of the same type (vol. = 0.6 cm^3, diam.=6 mm) were compared. Although the N_c factors for ^{60}Co were different (1.01,1.04,1.05, 1.06 and 1.08), the observed C_E values as a function of electron energy were the same for all the chambers, within the limits of reproducibility of the measurements.

II EVALUATION OF THE IMPORTANCE OF ION RECOMBINATION IN IONIZATION CHAMBERS EXPOSED TO HIGH DOSE-RATES

With the higher dose-rates actually available with modern electron beam generators, ion recombination needs te be taken into account for the usual ionization chambers. The main reason is that one deals with pulsed radiation; moreover, when an electron beam is "scanned" over the irradiation field, the ratio is still higher between the "instantaneous" dose-rate (or the dose per pulse) and the "average" dose-rate(which is measured).

Correction factors for ion recombination can reach several per cents in treatment conditions, and even more during calibration procedures or biological irradiations.(We only consider here conditions close to those encountered in the therapy, we do not consider the"very high dose-rates" which can be obtained with special linear accelerators).

For the data presented in Table I, the dose-rates used were low, so that corrections for ion recombination in the chamber were small or could be neglected.A maximum correction of 1% had to applied (Ref.6).Correction factors for ion recombination in a chamber can be determined theoretically or experimentaly.In a first set of experiments, the correction factors were determined from the variation of the dose meter reading associated with a variation of the voltage applied to the chamber (DUFREIX A. and COHEN L.,unpublished data,1975).The results were in a good agreement with the theoretical calculations derived from the formula proposed by BOAG (Ref.13).

In a second set of experiments, the readings of a commercially available Nuclear Enterprises chamber were compared with the response of the $FeSO_4$ dose meter,since it is assumed that the response of the latter is dose-rate independent up to 2×10^6 $Gy.s^{-1}$ (Ref.2).

These measurements were performed with the Sagittaire linear accelerator of the Institut Gustave-Roussy.In this accelerator 100 pulses of 3-μs duration are emitted per second, and the irradiated field is "scanned" by the electron beam with a frequency of 0.6 s^{-1}.Because of the scanning system, the ratio between the average dose-rate and the instantaneous dose-rate is complex and depends on electron energy, as the size of the primary pencil beam varies with electron energy.

Our results are presented in Table II which shows that correction factors derived from comparison with $FeSO_4$ are in good agreement with those obtained by variation of the ionization chamber voltage.Figure 1 compares our experimental C_E values taken from Tables I and II with a theoretical curve derived from Fig 3.7 of Ref.2.

A systematic study of recombination has been performed more recently by MARINELLO and Coll. (Ref.14).This work has shown for example that in a 30 MeV electron beam produced by a linear accelerator Sagittaire, the ion recombination in a Nuclear Enterprises chamber was about 7% at a mean dose rate of 1.7 Gy but reached 16% at a mean dose rate of 3.8 Gy.

III USE OF THE $FeSO_4$ DOSEMETER FOR DETERMINATION OF ABSORBED DOSE IN BIOLOGICAL SAMPLES

The previous paragraphs dealt with absorbed dose measurements at the level of the maximum of the depth/dose curve, where the depth/dose curve is relatively flat ("plateau region").Determination of absorbed dose in depth raises several problems.Accurate depth/dose determinations are needed for studies of RBE as a function of electron spectrum in depth in a high-energy electron beam (Ref.12).

First of all, the response of an ionization chamber (esu/Gy) varies with depth since electron energy decreases. As a consequence a correction related to electron energy has to be applied.This assumes that the electron energy at the point of interest in known with accuracy,

The second problem concerns the point of measurement of the ionization chamber.One can admit that, in an electron beam, the point to which the dose is to be referred lies between the anterior wall and the center of the chamber so that the uncertainty about its position is, at most, equal to the radius of the chamber.Using cylindrical chambers of various diameters (Fig 2), irradiated perpendicularly to their axis,DUTREIX and DUTREIX (Ref.15) found that in a 20-MeV electron beam the point of measurement lies in front of the center at a distance of 2/3 of the radius.However, this distance may vary with the electron energy, the depth and the type of chamber (diameter of air cavity and of central electrode etc.).HETTINGER et al. (Ref.18) found a distance of 3/4 of the radius in front of the center in electron beams produced in a 35-MeV Brown Boveri betatron.

When the dose is rather uniform in the "plateau region" this is of little importance, but when the dose gradient is high this can introduce considerable errors.For example, at the 30% isodose level in a 20-MeV electron beam, a change in depth of 1mm corresponds to a change of about 10% in the absorbed dose.

A $FeSO_4$ dosemeter does not present such disadvantages:

(1) It can be assumed to be insensitive to energy variation in depth (or dose-rate variation)
(2) It does not introduce any heterogeneity and no displacement factor has to be applied;

(3) The dosemeter solution can be used in thin layers (a few mm) or can occupy a volume identical to that of the biological systems to be irradiated (for example suspensions of bacteria, yeast, etc.) in order to avoid any "geometrical" error (see Figs 3,4,5 and 6).

However, a practical problem arises when the dosemeter solution is used in thin layers, for example in Perspex cells: it is important to avoid chemical reactions with the walls of the cells.Therefore the cells must be cleaned very carefully and must be pre-irradiated at a high dose ($\simeq$ 1000 Gy).According to our experience, a reproducibility of better than 1% can be achieved with these precautions (Ref.12).

IV THE USE OF $FeSO_4$ AS A TRANSFER DOSIMETER.

One of the most interesting applications of the Fricke dosemeter is its use as a transfer dosimeter for comparisons between different radiotherapy centres.The advantages of such comparisons in maintaining consistency are generally recognised and it is for this type of application that IAEA is indeed mainly interested in the $FeSO_4$.

As far as our experience with intercomparisons is concerned, we performed in 1973 (Ref.21) a comparison of the dosimeter calibration for ^{60}Co. Twenty centres (from France, Belgium and Switzerland) took part to the study.Each centre received 6 $FeSO_4$ samples to irradiate at doses ranging from 70 to 150 Gy.The mean of the standard errors observed for each centre was about 0.5% which indicates the high level of reproducibility of the method. This reproducibility was at least equal to, or better than, that achieved by other groups with $FeSO_4$ or with other techniques (Ref.22 , 23).

As already reported in detail, 2/3 of the centres were within $\pm$ 2% from the mean.Three centres differ by 3 to 5% and five centers differ by more than 5%.Our solution samples have not been mailed, but have been distributed taking opportunity of meetings or travels of some members of the different centres.

In a second series of experiments (Ref.24), $FeSO_4$ was used to compare our dosimetry with Edinburgh.Furthermore,as the two centres were using $FeSO_4$, this opportunity was taken to compare the responses of the solutions and the spectrophotometer (value of ε).

The observed agreement was better than 1% for each compared parameter: absorbed dose, ε, and G.

CONCLUSION.

In conclusion, the $FeSO_4$ dose meter has certainly been the only available method for high-energy photon and electron dosimetry in radiotherapy centres for checking the results obtained with ionization chambers at a time when calibration coefficients and correction factors for the chamber readings were not definitively known or were incompletely understood.

When an $FeSO_4$ dose meter is available in a laboratory, it is useful to check the results of ionization dosimetry. It can be used either as an overall check of ionization dosimetry, or to check each parameter or coefficient independently (for example: C_E or C_λ factor, recombination factor, etc.).

As the response of an $FeSO_4$ dosemeter is directly related to the absorbed dose (for high-energy electron and photon beams) any error arising from an inaccurate evaluation of beam energy of the spectrum is avoided. The same remark applies when recombinations in ionization chambers are becoming important.

When an $FeSO_4$ dosemeter is not available in a laboratory (and we agree that great care is needed with $FeSO_4$ to obtain reproducible measurements), $FeSO_4$ can be used as a "transfer" dose meter and prepared and read by national and international laboratories.

Finally, in high-energy electron radiobiology, $FeSO_4$ is probably the most suitable dosimetric system to determine absorbed dose in biological systems.

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TABLE I. C_E AND C_λ VALUES FOR DIFFERENT ELECTRON AND PHOTON ENERGIES DETERMINED BY COMPARISON WITH $FeSO_4$

Type of electron generator	Energy of the incident electron beam (E_o/MeV)	Depth of the point of measurement ($d/g.cm^{-2}$) (a)	C_E measured for a Nuclear Enterprises chamber (b)	C_E recommended values (d)
Allis-Chalmers betatron	10.0	2.1	0.881 ± 0.008 (c)	0.895
"Sagittaire" linear accelerator	10.0	2.0	0.888 ± 0.019	0.893
Brown-Boveri betatron	14.7	1.8	0.871 ± 0.009	0.857
Allis-Chalmers betatron	19.0	2.1	0.843 ± 0.005	0.841
Brown-Boveri betatron	29.0	2.1	0.813 ± 0.005	0.810
Brown-Boveri betatron	33.0	2.1	0.802 ± 0.010	0.800

Type of generator	Energy	C_λ measured for a Nuclear Enterprises chamber (b)	C_λ recommended values (e)
^{60}Co	1.25 MeV gamma-rays	-	0.95
Allis-Chalmer betatron	21 MV X-rays	0.910 ± 0.008	0.90

(a) Measurements made in Perspex. The point of measurement is assumed to be at a distance of 2/3 of the radius in front of the centre of the chamber (Ref.15).

(b) Assuming a constant G-value for ^{60}Co and the different beams.

(c) p = 0.05

(d) Interpolated between values given in Table 6.2 by ICRU (Ref.2).

(e) ICRU Report n° 23 (Ref.25).

TABLE II. ION RECOMBINATION IN A NUCLEAR ENTERPRISES CHAMBER (APPLIED VOLTAGE 225 V) EXPOSED TO HIGH DOSE-RATES OF HIGH-ENERGY ELECTRONS[a]

Energy of the incident electron beam (E_o/MeV)	Depth of the point of measurement ($d/g.cm^{-2}$)[b]	C_E recommended values[c]	Recombination factors determined by : Comparison with $FeSO_4$[d]	Variation of chamber voltage
11.5	1.7	0.878	1.04 ± 0.02	1.05
14.2	3.0	0.878	1.03 ± 0.01	1.05
31.6	3.0	0.812	1.13 ± 0.01	1.11

(a) Sagittaire linear accelerator. Average dose-rates 4.4 , 4.2 and 4.3 $Gy.min^{-1}$ for 11.5 , 14.2 and 31.6 MeV respectively.

(b) The point of measurement is assumed to be 2/3 of the radius in front of the center of the chamber (Ref.15).

(c) Interpolated between values given in Table 6.2 by ICRU (Ref.2).

(d) Assuming a constant G-value for ^{60}Co and electrons at the dose-rates used. Confidence interval (p=0.05) calculated from statistical fluctuation of ratios of readings of the chamber and the $FeSO_4$ dosemeter.

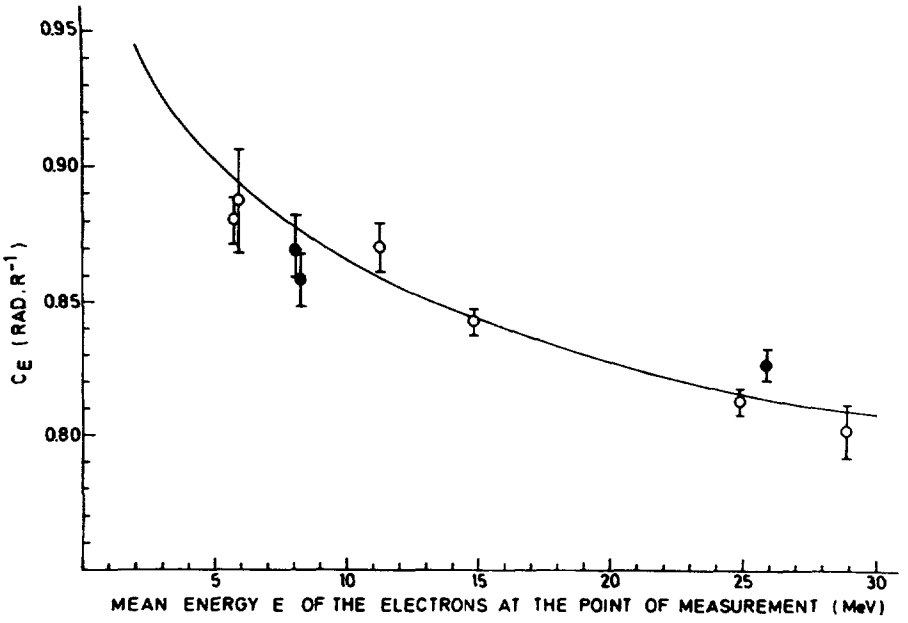

Fig.I. Absorbed dose conversion factors C_E (see text, Eq.(1)) determined for a Nuclear Enterprises ionization chamber by comparison with $FeSO_4$. The open and solid circles correspond to the data of Table I and II respectively. The mean energies E of the electrons are calculated by the Harder's formula $E = E_o\ (1-d/R_p)$ (Ref.16). The theoretical curve is derived from Fig. 3.7 of (Ref.2). From Wambersie and Coll., 1975 (Ref.17).

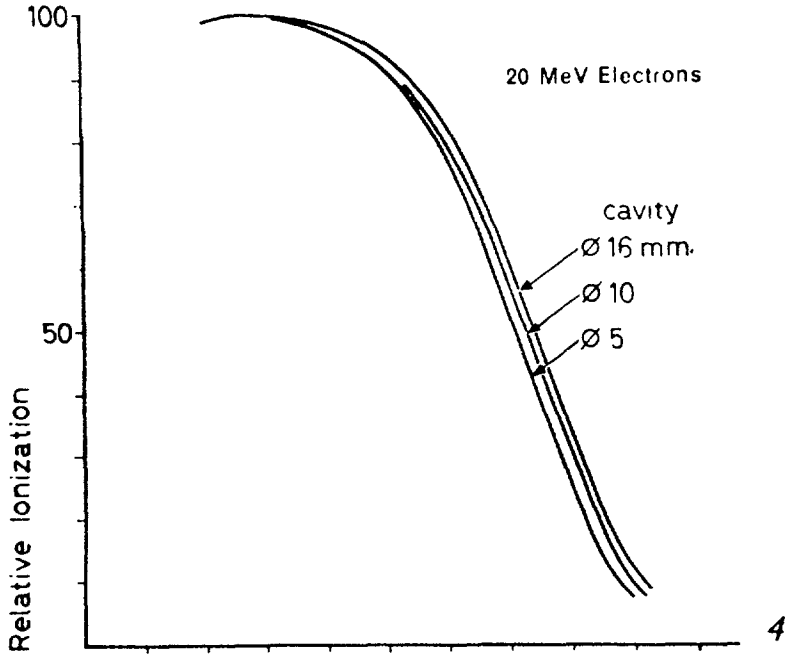

Fig. 2. Depth ionization curves obtained in a 20 MeV electron beam with cylindrical chambers of the same type (grooved in Perspex) but of different diameters, irradiated perpendicularly to their axis. From the extrapolation of these data to "zero diameter", the displacement factor (see text) can be obtained (Ref.15).

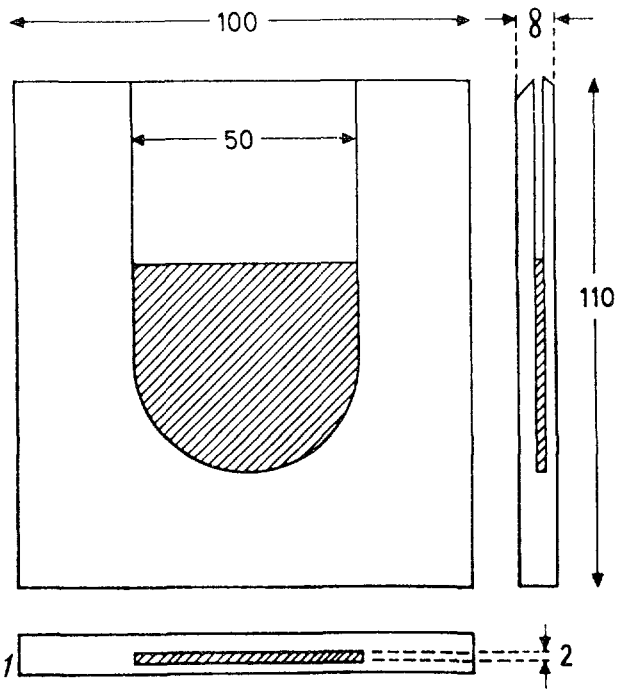

Fig. 3. Perspex cell used for the irradiation of $FeSO_4$ or microbiological suspensions in identical geometrical conditions. The thickness of the cavity is 2 mm (Ref.19).

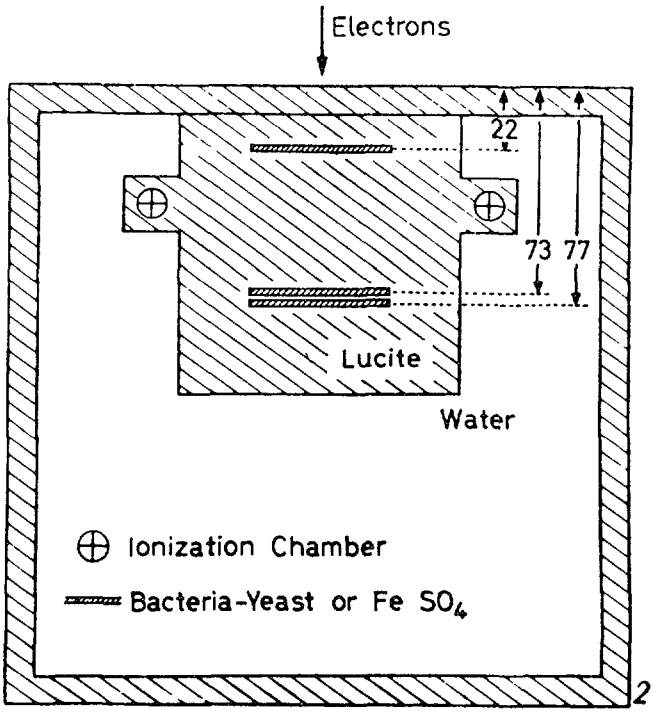

Fig. 4. Arrangement used for irradiation of $FeSO_4$ and biological systems in thin layers and in identical geometrical conditions. Horizontal section through the beam axis. The Perspex cells containing the "detectors" can be placed at different depths in the electron beam. Two ionization chambers are used as "monitors" (Ref.19).

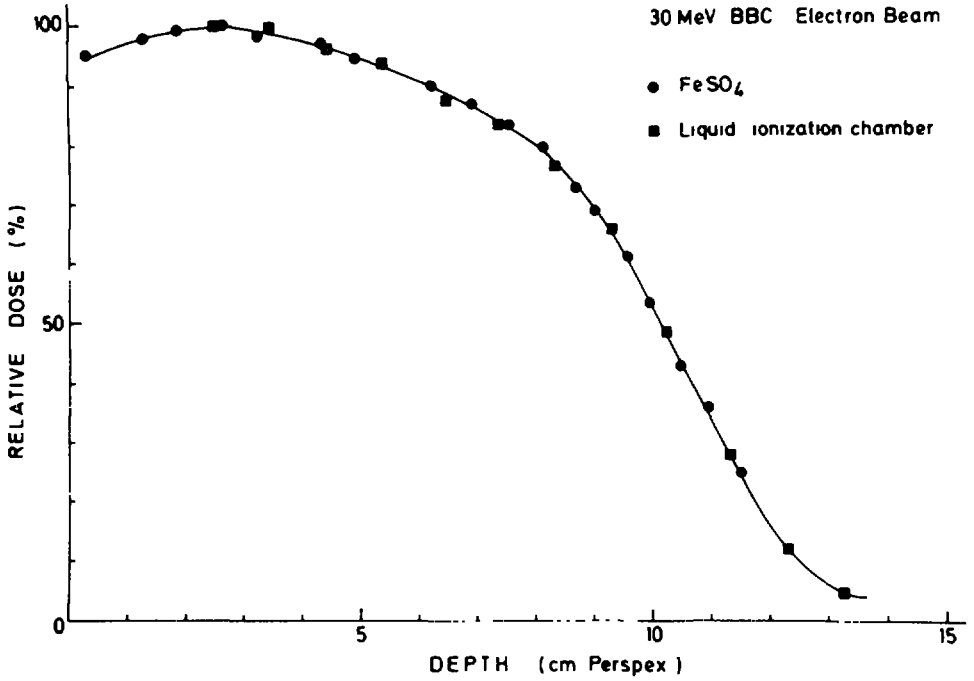

Fig. 5. Comparison of depth/dose curves measured, in a 30 MeV electron beam, with $FeSO_4$ and a liquid ionization chamber. $FeSO_4$ solution is irradiated in conditions illustrated on Fig. 3 and 4. The parallel plate liquid ionization chamber is filled with trimethyl-pentane (thickness of the liquid : 0.9 mm). This chamber does not introduce heterogeneity and no displacement factor has to be applied; it can be assumed to be insensitive to energy variation in depth (Ref.20). A close agreement is reached between the curves obtained with these two techniques.

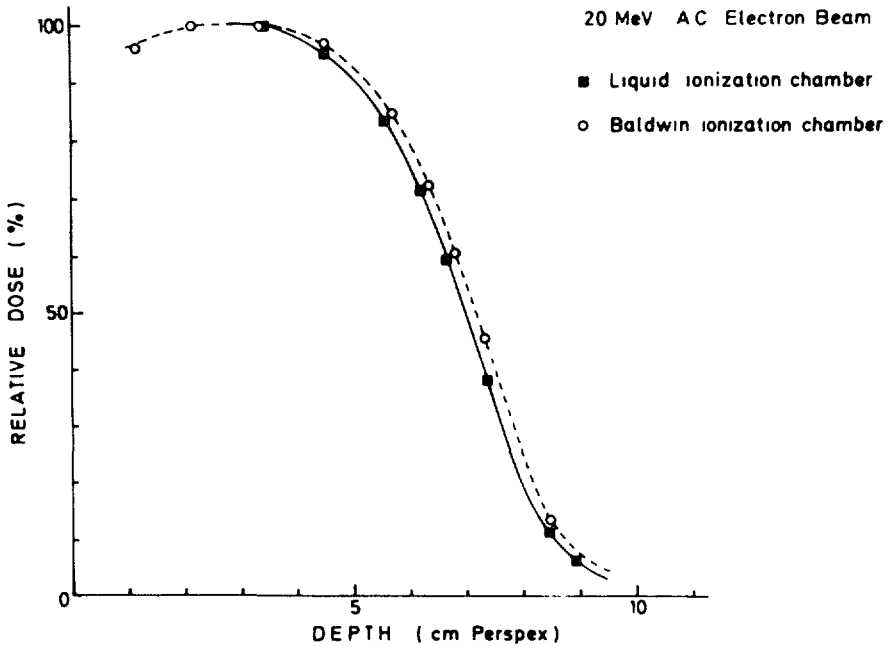

Fig. 6. Comparison of depth/dose curves measured, in a 20-MeV electron beam, with a Nuclear Enterprises (Baldwin) ionization chamber and a liquid ionization chamber (Ref.20). The readings of the Nuclear Enterprises chamber are corrected only for the variation of its response as a function of electron energy in depth (see text). No correction is applied to the liquid ionization chamber readings (Fig.5). The discrepancy observed between the two curves (≃ 2 mm) corresponds to the displacement factor of the Nuclear Enterprises chamber (2/3 of the radius) (Ref.15).

POSTAL DOSE INTERCOMPARISON FOR HIGH ENERGY X-RAYS AND ELECTRONS WITH TLD

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ABSTRACT

This study concerns the accuracy and precision of the IAEA/WHO LiF TLD system used in intercomparison by mail of absorbed doses from ^{60}Co γ-radiation, 4-25 MV X-rays, and 4-20 MeV electrons. The system employs 160 mg LiF powder in polystyrene capsules, which are placed at 5 or 7 cm depth in water for ^{60}Co γ-radiation and high energy X-rays and at 10 to 12 cm depth in water for 4-20 MeV electrons and irradiated to doses close to 200 rad (2.00 Gy). The dosimeters are mailed to the IAEA Dosimetry Laboratory and read out under conditions to minimize variations in instrument sensitivity. The precision of the readout technique, using 3 capsules per irradiation and the readout of 5 aliquots per capsule, is characterized by 0.2% standard deviation of the resulting mean. Since random errors during the irradiation are added, the detectable systematic discrepancy in dose delivery, at the 95% confidence level, is ± 2% for ^{60}Co, ± 3% for high energy X-rays, and ± 3% for 12-20 MeV electrons. For electrons of 7-11 MeV energy, the detectable difference is estimated, on less solid grounds, to be about ± 5%. However, the latter figure may be expected to be reduced if the energy dependence in this range can be determined with

higher accuracy. At 4 MeV or lower energy, considerable difficulties can be expected due to energy dependence and random errors. The response of the LiF dosimeter to X-rays and electrons, compared with that for ^{60}Co γ-radiation, was determined to decrease from 1.00 for 4 MVX-rays to 0.98 for 25 MV X-rays and to 0.96 for 12-20 MeV electrons.

INTRODUCTION

The IAEA/WHO has, for several years, conducted a postal dose intercomparison service for ^{60}Co γ-radiation with thermoluminescence dosimeters (TLD).[1,2] The purpose of this activity has been to intercompare the absorbed doses given with ^{60}Co radiotherapy machines at different institutions and, by informing the participants of their results, to improve the accuracy of the clinical delivery of the radiation dose. The participants have been asked to irradiate polystyrene capsules containing 160 mg LiF powder to a known absorbed dose in water. The dosimeters have then been sent to Vienna through WHO channels, and read out at the IAEA dosimetry laboratory, which, based on its own calibration, has assigned a certain "measured dose" to the dosimeter. This measured dose is then compared with the "stated dose", i.e. the dose to the capsule estimated by the participant. The stated accuracy for this intercomparison service is better than $\pm$ 5% at the 95% confidence level.

This TLD intercomparison service has been extended to orthovoltage dosimetry. In this energy range, the energy dependence of the LiF dosimeters introduces an additional complication but pilot studies have shown that intercomparisons can be performed with an accuracy of better than $\pm$ 10%.[3]

The purpose of the study reported here has been to evaluate the feasibility of applying the same technique for high energy X-rays in the energy range 4-25 MV and for high energy electrons in the energy range 4-20 MeV. The usefulness of such dosimetry intercomparisons is determined by the accuracy that can be achieved, i.e. the confidence with which a discrepancy between "measured dose" and "stated dose" can be attributed to a systematic difference in calibration of machine output and dose delivery between the participating institutions. Errors that tend to interfere with the detection of such differences originate partly in the short- and long-term variations in the TLD instrument sensitivity, including variations in the amount of LiF powder used for each measurement.

These errors can be minimized by carefully selected procedures but not completely eliminated. In addition, the calibration methods used by the IAEA Dosimetry Laboratory must be considered. Finally, the irradiation of the dosimeters at the participating institution is subject to random errors in machine function, instrumentation used for calibration, and positioning of the dosimeters. The present study aims towards assessing the magnitudes of these effects. When comparing different radiation qualities, such as X-rays and electrons of various energies, the possibility of an energy dependent response of the TLD cannot be excluded. An effort has been made to extract this information from the data collected in the experiments reported here.

METHODS

1. TLD Techniques

The dosimeters consisted of polystyrene capsules of 5 mm external diameter, containing 160 mg of LiF powder (TLD-700, Harshaw Chemical Co.). All the LiF powder, used in any one of the experiments, was from the same virgin batch of powder, annealed at 400°C for 1 hour and at 80°C for 24 hours before distribution. When returned to the IAEA Dosimetry Laboratory after irradiation, the powder did not receive additional annealing since at least four weeks lay between irradiation and readout, and the signal related to unstable traps in the LiF had therefore been eliminated.

The powder in each capsule was divided into 5 aliquots, using a vibrating dispenser. The aliquots were read out in a Harshaw 2000A and B TLD readout instrument. The readouts of the experimentally irradiated dosimeters were interspersed with readouts of a reference powder, irradiated in a $^{60}Co\ \gamma$ beam as a large batch at one time under conditions to ensure uniformity. Five aliquots of the reference powder were read out each time. The average signal from the two bracketing readouts of the reference powder was used as a relative measure of the instrument sensitivity, applicable for the capsules that were read out in between.

2. Experimental Irradiations

The institutions participating in this study have been the Joint Center for Radiation Therapy (JCRT) and Massachusetts General Hospital (MGH), both of Boston, Massachusetts, USA, and Sahlgren Hospital (SH), Göteborg, Sweden.

In each experiment, the participants irradiated three capsules each with ^{60}Co γ-radiation with various X-ray beams in the energy range 4-25 MV and with various electron beams in the energy range 4-20 MeV. The capsules were irradiated one at a time, but the same setup and output calibration were used for any one radiation quality. During the irradiations, the plastic capsules with the LiF were placed in water at 7 cm depth for 25 MV X-rays and 5 cm depth for ^{60}Co and the other high energy X-ray beams, For electrons, the capsules were placed in water at 1 cm depth for 4 and 7 MeV and 2 cm depth for other energies. A plastic rod was used to hold the dosimeters in position, as shown in Figure 1. This arrangement is the same as used in the IAEA/WHO ^{60}Co postal dose intercomparison service.[2]

3. Determination of Absorbed Dose

The output from the radiation units was always calibrated by measurements with ionization chambers at the time of irradiation. The measured ionization was converted to absorbed dose using the C_λ and C_E factors (Table IV). Comparisons between JCRT and MGH were made during the experiments. Some further details of the calibration procedures used by the institutions are given below.

JCRT irradiated with 8 MV X-rays, 4 and 7 MeV electrons from a Siemens Mevatron 12 linear accerlerator and with 4 MV X-rays from a Varian Clinac 4 linear accelerator, in addition to the irradiation with ^{60}Co. The calibration technique for ^{60}Co was somewhat different in different experiments: the institution measured the dose rate in air with a 0.5 cm^3 Exradin A-1 ionization chamber, in polystyrene with the same chamber, or in water with a 0.35 cm^3 PTW 30-312 chamber. Both chambers have air-equivalent plastic walls. For 4 MV and 8 MV X-rays, the calibrations were made either in polystyrene with the Exradin ionization chamber, or in water with the PTW instruments or with a Capintec model PO.6 chamber. The electron calibrations were made in water with the PTW instruments. The ionization chambers used were either calibrated by National Bureau of Standards (NBS) and controlled by constancy checks, or calibrated against such an instrument at the time of the experiment. In all cases, either a Keithley 610C or 616 electrometer was used.

MGH irradiated with 10 and 25 MV X-rays and 12, 15 and 18 MeV electrons in addition to ^{60}Co. The X-ray beams were provided by Varian Clinac 18 and

Clinac 35 linear accelerators respectively, and the electron beams were provided by Varian Clinac 18. The MGH used a 0.6 cm^3 Farmer ionization chamber (Nuclear Enterprises 2505/3) with a graphite thimble and a Keithley 616 electrometer for the calibrations. This chamber had been calibrated by NBS for ^{60}Co γ radiation. The initial determination of the output from the MGH ^{60}Co unit was based on a series of five measurements over a six week period. The first three calibrations were in air, the remaining two in water. Measurements of the output in water for ^{60}Co were made again at the time of the TLD irradiations and compared with the calculated decay. Agreement was always better than 1%. The measurements for X-rays and electrons were made in water.

SH participated in only two experiments compared with the five of the other two institutions. In addition to irradiations with the ^{60}Co beam, dosimeters were exposed to 5 MV X-rays from an AEI linear accelerator and 8 MV and 16 MV X-rays and 10, 14, 17 and 20 MeV electrons from a Philips SL 75/20 linear accelerator. The SH reference instrument was a Farmer (Nuclear Enterprises 2505/3) ionization chamber, calibrated at the National Institute for Radiation Protection in Stockholm. A Therados RDM 2 electrometer was used. All calibrations were made in water.

IAEA Dosimetry Laboratory irradiated a set of fifteen capsules for the purpose of calibrating the sensitivity of the TLD system. The absorbed doses selected were in the range of 175-225 rad (1.75-2.25 Gy). These irradiations were performed with a Picker ^{60}Co teletherapy unit, within one week of the experimental irradiations. An NPL Secondary Standard Level X-ray Exposure Meter, Type 2560, and an NPL Secondary Standard Chamber, Type 2561, with a calibration factor obtained from the National Physics Laboratory (NPL), United Kingdom, were used for the output calibration. Some additional details of the calibration have been published elsewhere.[4] These calibration capsules were read out under the same conditions and at the same time as the experimentally irradiated capsules. The calibration factor was determined using a least square, linear fit to the resulting TLD signals (normalized by the readings from reference powder) vs. absorbed dose in water.

RESULTS

For each capsule, 5 aliquots were read out and corrected for instrument sensitivity using the reference powder in the manner described above.

In the following, the resulting values are called y_{ijk}, where index i denotes the sequential number of the aliquot for each capsule (i = 1, 2, 3, 4, 5), index j the sequential number of the capsule in the experiment (j = 1, 2, 3), and k identifies the experiment (energy, institution, date). The standard deviation of the sample in each set of five readouts per capsule was calculated as

$$s_{jk}^2 = \frac{1}{4} \sum_{i=1}^{5} (y_{ijk} - \bar{y}_{jk})^2 \quad (1)$$

where $\bar{y}_{jk}$ is the mean of the five readings for the capsule jk. The mean value of the readings for the three capsules in each experiment was then calculated:

$$\bar{y}_k = \frac{1}{3} \sum_{j=1}^{3} \bar{y}_{jk} = \frac{1}{15} \sum_{i=1}^{5} \sum_{j=1}^{3} y_{ijk} \quad (2)$$

The mean standard deviation of the sample for the three capsules in each experiment was also calculated as

$$\bar{s}_k = \frac{1}{3} \sum_{j=1}^{3} s_{jk} \quad (3)$$

as well as the range for the three capsules

$$r_k = \max \bar{y}_{jk} - \min \bar{y}_{jk} \quad (4)$$

Tables I and II list the values of $r_k/\bar{y}_k$ for the various experiments and the average relative standard deviation $\bar{s}_k/\bar{y}_k$, both expressed as percentages.

The measured values x_{ijk} for the ^{60}Co irradiated calibration dosimeters, corrected using the reference powder as described, were used in the following way. The mean value for each capsule was calculated, $\bar{x}_{jk}$. The dose to which the capsule was irradiated is called c_{jk}. A linear fit

$$\bar{x}_{jk} = a_k + b_k c_{jk} \quad (5)$$

was determined, using a least square program, with the data set $\{\bar{x}_{jk}, c_{jk}\}$. For each group of experiments pertaining to a particular date in Tables I, II and III the parameters a_k and b_k may be different.

The mean values $\bar{y}_k$ for each experiment were converted to "measured dose" d_k, from the relation

$$\bar{y}_k = a_k + b_k d_k \quad (6)$$

Strictly, d_k is the absorbed dose in the ^{60}Co γ beam, calibrated by the IAEA, which would be expected to give the average value $\bar{y}_k$. The "measured dose" d_k was finally divided by the "stated dose" D_k, i.e. that dose to which the participant institution claimed to have irradiated the capsules.

This gives the ratio

$$R_k = d_k/D_k \qquad (7)$$

Tables I and II include the values of R_k for the various experiments.

For each of the three participating institutions, the average of these ratios R_k was calculated for the ^{60}Co and the X-ray beams employed. These values $\bar{R}$ are presented in Table IV. For the two institutions that performed 5 separate experiments for each radiation quality used, the standard deviation of these 5 samples was also calculated, using the same kind of formula as eq. (1). The resulting values can be seen in Table IV. This calculation was not performed for SH, since this participant took part in only 2 experiments.(and for the experiments with electrons for the same reason)

DISCUSSION

1. Precision of the readings

The sources of variations that manifest themselves in the estimated standard deviation s_{jk} are primarily differences in the exact amount of LiF powder in the aliquots dispensed for the five readings for each capsule and short-term fluctuations in the sensitivity of the readout instrument.

The average of all the $\bar{s}_k/\bar{y}_k$ values in Tables I and II is 0.77%. In the absence of any capsule-to-capsule effects (see below), this is the best estimate from the measured data of the relative standard deviation when reading aliquots taken from capsules which have been irradiated identically. The values $\bar{s}_k$ and s_{jk} closely follow normal distributions. Thus, the standard deviation of the mean of the five readings for each capsule would be expected to be $0.77/\sqrt{5} = 0.34\%$.

2. Precision of the capsule values

If all three capsules in each experiment were identical in all respects, including irradiation and readout, the only source of variation among the mean values of five readouts per capsule would be the short-term variations discussed above. Thus, the relative range $r_k/\bar{y}_k$ among the means for three capsules would be expected to be $\sqrt{3}$ times the standard deviation of the same mean[5] or $0.34\sqrt{3} = 0.59\%$. The average relative range for the n = 12 values

for ^{60}Co γ beams in Table I is 0.64% and the corresponding figure for the X-ray irradiations is 0.63% (n = 26). From this, it is concluded that the capsules were irradiated in a reproducible manner with X-rays as well as ^{60}Co γ. Sources of error that could have affected the ranges r_k among capsules but not the spread of readings for individual capsules are variations in actual exposure timing or in the accelerator monitor. Positioning variations could also have contributed.

Since no such errors appear to be introduced when irradiating the three capsules in each experiment, the standard deviation of the mean for the three capsules is the same as for fifteen aliquots, i.e. $0.77/\sqrt{15} = 0.34/\sqrt{3} = 0.2\%$

3. Precision of the experiments

Table IV shows the resulting average ratios $\bar{R}$ for each participant and radiation quality. In the case of MGH and JCRT for X-rays, this is based on five experiments and for electrons on two experiments; in the case of SH, on two experiments for X-rays and electrons. The results from the individual experiments are listed in Tables I, II and III as the quantity R_k. The standard deviations of these ratios R_k have been calculated, using a formula analogous to eq. (1), for the five values per radiation quality for the two Boston hospitals. The values for this standard deviation are somewhat higher for the X-ray experiments than for ^{60}Co, the mean values being 1.6% for X-rays and 1.0% for ^{60}Co.

In the following, it will be assumed that the difference between these variation for ^{60}Co and X-rays is significant. This is plausible, since there are additional sources of error that limit the reproducibility for irradiations with X-rays compared with ^{60}Co.

For ^{60}Co, the standard deviation of R_k was determined to be 1.0%. Of this, it has been previously shown that the standard deviation of the mean for the three capsules used is 0.2%. This was caused primarily by variations in the readout process, including the aliquots dispensed. These errors also pertain to the calibration dosimeters irradiated and read out by IAEA. Since 15 capsules (75 aliquots) were used for this purpose, the standard deviation of the quality b_k can be estimated as $0.77/\sqrt{75} = 0.2/\sqrt{5}$ (%). In

addition, there are variations in the geometrical setup and timing of the exposure. These occur at the IAEA Dosimetry Laboratory (τ_1) and at the participating institution (τ_2). This gives the relation

$$1.0^2 = 0.2^2 + (0.2/\sqrt{5})^2 + \tau_1^2 + \tau_2^2 \qquad (8)$$

It is reasonable to assume that $\tau_1 = \tau_2$, which means that eq. (8) can be solved with $\tau_1 = \tau_2 = 0.7\%$.

For the X-ray irradiations, the IAEA calibration procedures are the same and the $\tau_1 = 0.7\%$ determined remains valid. However, τ_2 is no longer the same but has changed to τ_{2x}. Thus, the total standard deviation of R_k(1.6%) can be divided as

$$1.6^2 = 0.2^2 + (0.2/\sqrt{5})^2 + 0.7^2 + \tau_{2x} \qquad (9)$$

and the random errors caused by the participant are thus estimated to be $\tau_{2x} = 1.4\%$.

4. Comparison among institutions

According to a t-test, neither the mean of the results from the twelve ^{60}Co experiments nor the mean of the ^{60}Co results from any one of the three institutions is significantly different from unity. Thus, it can be assumed that any systematic differences in the ^{60}Co calibration among the four participants are negligible compared with the random errors. These random errors are summarized by eq. (8) and add to a total of 1.0% relative standard deviation, as discussed above.

Figure 2 shows the values R_k (measured dose/stated dose) for the X-ray experiments as a function of the X-ray energy. It should be noted that the measured dose is that dose of ^{60}Co photons that would give the same TLD reading as was actually measured. The data in the figure indicate a slight decrease of this ratio R_k with increasing energy. The solid line in Figure 2 is a least square fit to the measured data and indicates that the ratio drops by about 2% from 4MV to 25 MV. These R_k values are influenced by the factor C_λ that the participants have chosen in the calculations of "stated dose". These C_λ values are indicated in Table IV. While the values are consistent among the participants, there are uncertainties in the C_λ values.[6]

Assuming that the C_λ values are correct, Figure 2 may be interpreted as indicative of a slight decrease of the TL response of the LiF dosimeter used with increasing X-ray energy in this range. The energy dependence of this type of LiF TL dosimeter for high energy X-rays has been studied by others. Almond and McCray[7] observed a lower response (0.93) for X-ray energies around 20 MV compared with that for ^{60}Co, while Mansfield and Suntharalingam[8], found less than 1% variation of the response to X-rays in the range 4-45 MV.

Electron irradiations

The energy of the electrons at the phantom surface was determined using the extrapolated range from depth ionization curves in water.

The electron irradiations by JCRT, March 1979, were performed at a time when the monitor chamber of the accelerator malfunctioned. An ionization chamber was inserted in the water next to the TLD capsule. At 4 MeV, the spread of the 5 readings per capsule is very much higher than for other irradiations, which is interpreted as evidence of some disturbance by the ion chamber. The resulting value of measured/stated dose has been rejected from the calculations.

Figure 3 shows the resulting quotients of measured to stated dose as a function of electron energy. From and including 12MeV, the data have a mean of 0.96 with a standard deviation of 1.0%. Thus, in this energy range the performance of the intercomparison system is similar to that for X-rays and ^{60}Co. However, the data were considered somewhat too uncertain, statistically to be included in Table IV. Below 12 MeV, the data are scattered. The reasons for this are not diagnosed at this time, but reflect, according to the preceding discussion of precision, some real differences in the irradiation of the dosimeters. Further experimentation is needed before the energy dependence below 12 MeV is ascertained with an accuracy comparable to that at higher energies. That the detectable systematic difference does not exceed $\pm$ 5% is made plausible by the data, presented in Figure 2. This is still small enough to allow clinically meaningful intercomparisons to be done.[9,10]

CONCLUSIONS

The IAEA/WHO TLD postal dose intercomparison system has been tested in this study. As with all measurement procedures, it is subject to systematic and random errors. In fact, the very purpose of the intercomparison is to detect systematic errors on the part of the participant.

For ^{60}Co, the precision in one experiment, consisting of the irradiation of three capsules, can be expressed as a relative standard deviation of 1% (Table IV). This implies that a value outside 0.98-1.02 with 95% probability reflects a systematic difference in absorbed dose determination between the IAEA and the participant. This takes into account a certain random error by the participant. The TLD technique itself is somewhat more precise, as was discussed in connection with eq. (8). The result that 2% is a significant discrepany at the 95% confidence level, should be compared with previous statements that 5% is needed to reach this level of confidence. [1]

For high energy X-rays, the random errors introduced by the participating institution seem to be somewhat higher than for ^{60}Co as was shown by eq. (9). To detect a systematic difference in absorbed dose determination between the IAEA and the participant at the 95% confidence level requires that the discrepancy exceeds 3%. This is supported by the fact that the standard deviation of the measured values, divided by the corresponding values on the curve in Figure 2, is 1.4%. The statement that 3% is a significant discrepancy presupposes that the IAEA conversion of the TLD reading to absorbed dose in water is based on the curve in Figure 2, and that there is no significant systematic error in this curve. Furthermore, the statement that a 3% discrepancy implies a 95% probability that a systematic difference exists, is of course not valid if the participant introduces greater random errors in the irradiation of the dosimeters than was the case in the experiments reported here.

There was no indication in this study of a systematic difference in absorbed dose determination between the hospitals in Boston and the one in Sweden. While JCRT and MGH compared the dosimetry procedures as part of the experiments, they had not previously intercompared dosimetry with SH.

For electrons of 12-20 MeV energy, no energy dependence seems to be present. The precision is similar to that for X-rays. Between 7 and 12 MeV, the uncertainty in the energy dependence remains considerable, but a detection limit of ± 5% is consistent with the experimental results. Below 7 MeV sufficient data are not available and there are physical reasons to expect great difficulties in performing meaningful intercomparisons at these low electron energies.

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TABLE I

The results of the experiments with ^{60}Co γ

Institution	Date	R_k, the ratio of measured dose to stated dose	$r_k/\bar{y}_k$, the range of average reading for 3 capsules, %	$\bar{s}_k/\bar{y}_k$, the average relative S.D. for 5 readings per capsule,%
JCRT	June 1978	1.022	1.6	0.86
	Oct. 1978	1.016	0.4	0.68
	Nov. 1978	1.003	0.6	0.73
	Feb. 1979	0.998	0.8	0.72
	May 1979	0.997	0.2	0.65
MGH	June 1978	0.999	0.3	0.90
	Oct. 1978	1.007	0.4	0.77
	Nov. 1978	1.018	0.2	0.68
	March 1979	0.998	2.3	0.48
	May 1979	0.991	0.2	0.48
SH	March 1979	1.001	0.6	0.68
	May 1979	1.006	0.1	0.70

TABLE II

The results of the experiments with X-rays

Energy	Institution	Date	R_k, the ratio of measured dose to stated dose	$r_k/\bar{y}_k$, the range of average reading for 3 capsules,%	$\bar{s}_k/\bar{y}_k$, the average relative S.D. for 5 readings per capsule,%
4 MV	JCRT	June 1978	0.975	0.2	0.88
		Oct. 1978	0.996	0.5	0.70
		Nov. 1978	1.000	0.6	0.68
		Feb. 1979	1.003	1.4	0.73
		May 1979	0.999	0.0	0.49
5 MV	SH	March 1979	0.995	0.9	1.16
		May 1979	0.991	0.5	0.83
8 MV	JCRT	June 1978	0.978	0.4	1.50
		Oct. 1978	0.988	1.6	0.81
		Nov. 1978	0.998	0.3	0.73
		Feb. 1979	1.000	1.5	0.81
		May 1979	1.036	0.2	0.85
8 MV	SH	March 1979	0.987	0.1	0.79
		May 1979	0.990	0.5	0.85
10 MV	MGH	June 1978	0.998	1.3	0.74
		Oct. 1978	1.001	0.8	0.71
		Nov. 1978	1.005	0.4	0.99
		March 1979	0.982	0.3	1.01
		May 1979	0.978	0.1	0.43
16 MV	SH	March 1979	0.975	0.8	1.02
		May 1979	0.978	0.1	0.72
25 MV	MGH	June 1978	0.969	1.8	0.54
		Oct. 1978	0.978	1.2	0.66
		Nov. 1978	1.013	0.6	0.65
		March 1979	0.983	0.1	0.74

TABLE III

The results of the experiments with electrons

Energy	Institution	Date	R_k, the ratio of measured dose to stated dose	$r_k/\bar{y}_k$, the range of average reading for 3 capsules, %	$s_k/\bar{y}_k$, the average relative S.D. for 5 readings per capsule, %
4 MeV	JCRT	March 1979	(1.008)	(2.4)	(5.0)
		May 1979	1.396	2.3	1.33
7 MeV	JCRT	March 1979	1.029	2.6	1.28
		May 1979	1.014	0.4	0.65
10 MeV	SH	March 1979	0.937	0.4	0.93
		May 1979	0.972	0.1	0.55
11 MeV	JCRT	March 1979	1.049	0.5	1.17
		May 1979	1.009	0.8	0.69
12 MeV	MGH	March 1979	0.956	0.3	0.82
		May 1979	0.944	1.2	0.76
14 MeV	SH	March 1979	0.955	0.7	1.06
		May 1979	0.952	0.1	0.66
15 MeV	MGH	March 1979	0.960	0.2	1.00
		May 1979	0.960	0.5	0.42
17 MeV	SH	March 1979	0.950	0.4	1.10
		May 1979	0.956	0.1	0.66
18 MeV	MGH	March 1979	0.979	0.2	0.60
		May 1979	0.952	0.2	0.57
20 MeV	SH	March 1979	0.968	1.2	0.75
		May 1979	0.958	0.2	0.83

TABLE IV

Summary of the results

Radiation	Institution	R, the average ratio of measured to stated dose	Estimated relative standard deviation of R_k, %	C_λ
^{60}Co γ rays	JCRT	1.007	1.1	0.95
	MGH	1.002	1.0	0.95
	SH	1.004	—	0.95
4 MV X-rays	JCRT	0.995	1.1	0.94
5 MV X-rays	SH	0.993	—	0.94
8 MV X-rays	JCRT	1.000	2.1	0.93
	SH	0.988	—	0.93
10 MV X-rays	MGH	0.991	1.2	0.93
16 MV X-rays	SH	0.977	—	0.92
25 MV X-rays	MGH	0.985	1.8	0.90
				C_E
7 MeV electrons	JCRT	1.022	—	0.89
10 MeV electrons	SH	0.954	—	0.885
11 MeV electrons	JCRT	1.029	—	0.88
12 MeV electrons	MGH	0.950	—	0.874
14 MeV electrons	SH	0.954	—	0.86
15 MeV electrons	MGH	0.960	—	0.859
17 MeV electrons	SH	0.953	—	0.85
18 MeV electrons	MGH	0.965	—	0.848
20 MeV electrons	SH	0.963	—	0.84

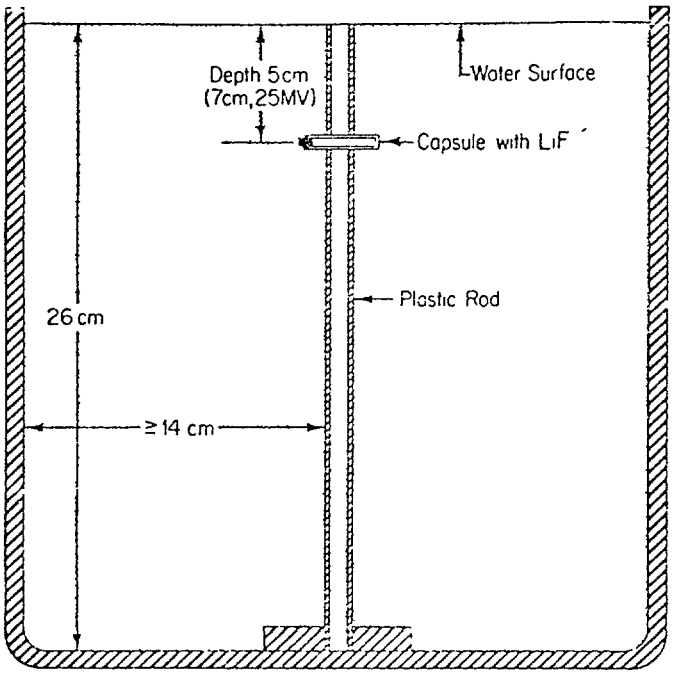

Figure 1

The setup used for ^{60}Co, X-ray and electron irradiations of the capsule containing LiF. The polystyrene capsule is 5 mm diameter x 30 mm long with 1 mm wall thickness. It contains 160 mg LiF. The plastic rod supporting the capsule is 1 cm diameter with 1 mm wall whickness. It extends to the surface of the water and the capsule is inserted into a hole through it at the appropriate depth. These depths were: ^{60}Co γ-rays and X-rays up to 20 MV,5 cm; 25 MV X-rays 7cm; 4 to 7 MeV electrons, 1 cm; 12-20 MeV electrons, 2 cm.

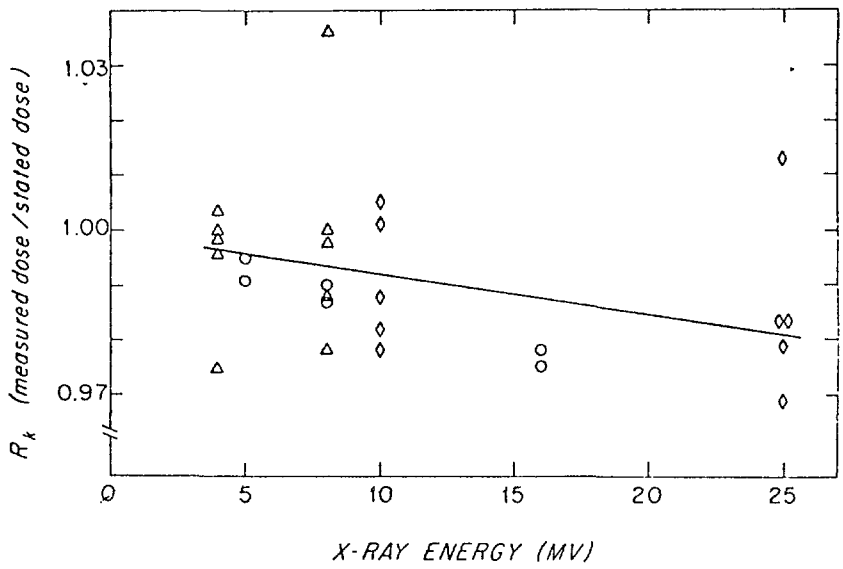

Figure 2

The results of the experiments, showing R_k, the measured ^{60}Co equivalent dose divided by the stated dose, as a function of X-ray energy. The measured dose is the average for the three capsules, irradiated by each participant in any one experiment. The data points show the results from the different experiments: triangles = JCRT, diamonds = MGH, circles = SH. The line is a least square linear fit to the data points.

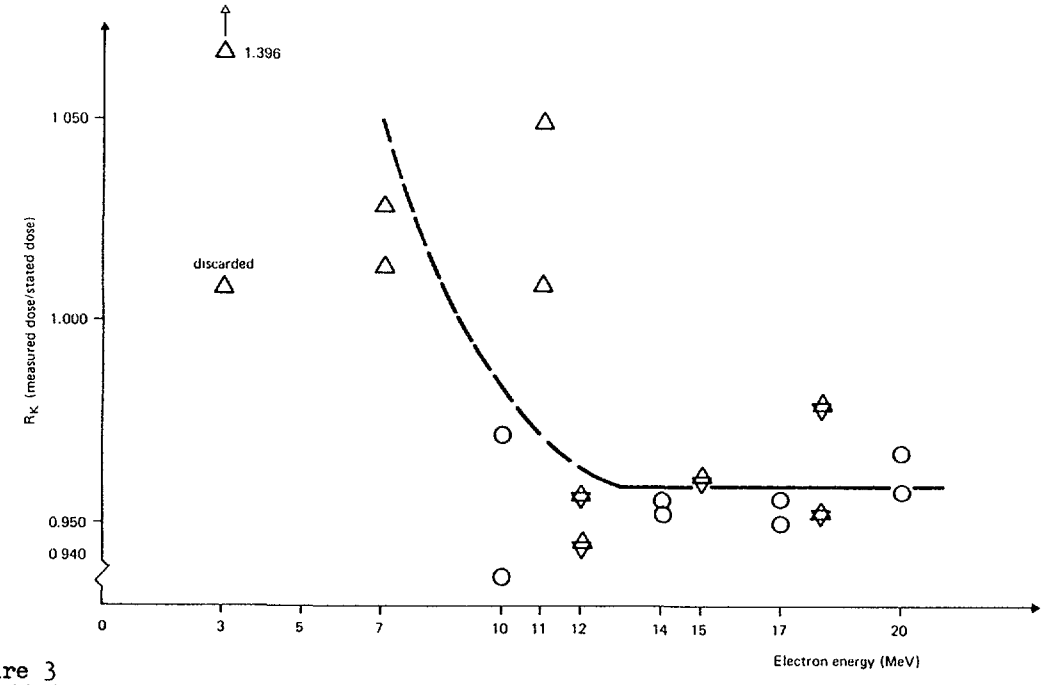

Figure 3

The results of the experiments, showing R_k, the measured ^{60}Co y equivalent dose divided by the stated dose, as a function of electron energy. The measured dose is the average for the three capsules, irradiated by each participant in any one experiment. The data points show the results from the different experiments: triangles = JCRT, diamonds = MGH, circles = SH.

ABSORBED DOSE DETERMINATION WITH IONIZATION CHAMBERS IN PHOTON AND ELECTRON BEAMS

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The International Commission on Radiation Units and Measurements (ICRU) has published general recommendations on dosimetry procedures for photon (ICRU 1969) and for electron beams (ICRU 1972). These have been supplemented by national or regional suggestions covering practical details of routine dosimetry procedures. In the Nordic countries such regional recommendations were published in 1972 (NACP 1972). These have now been revised (NACP 1980). There were several reasons for this revision. Since the first protocol several papers have been published giving new data on various effects of importance for the corrections used with ionization chamber dosimetry. The SI-units for the radiological quantities should be applied. The former Nordic recommendations were mainly based on investigations with betatrons, while within the Nordic countries now several other kinds of accelerators are used with usually different properties, which had to be considered.

The aim of the recommendations is to give hospital physicists a "code of practice" to be followed at all radiation therapy centres in the Nordic countries so as to secure uniformity of dosimetry procedures. In weighting high accuracy and theoretical strictness against practical usefulness, the latter was given more emphasis so that the procedures may be performed easily.

General concepts on dosimetry

The probe method

In order to measure the absorbed dose, D_m, given to matter of a medium, m, at a point of interest, P, a small piece of the medium centered at this point is replaced by the detector or the probe. Generally the probe consists of the radiation sensitive material, i, and in many cases also of a wall, container, or cover surrounding the sensitive material. The dimensions of the probe shall be chosen small enough to give the required spatial resolution of the measurement and to reduce, as much as possible under given requirements of probe sensitivity, any influence on the particle fluence at P when the probe is inserted. This general description of the probe applies

to all kinds of dosimeter systems, e.g., calorimetric dosimeters and ionization chambers as well as chemical, photographic, thermoluminescent and radiophotoluminescent dosimeters.

The performance of the probe method consists of two principal steps, namely:

1) The determination of the mean absorbed dose to the probe material, $\overline{D}_i$, from the dosimeter reading, using either the appropriate calibration factor or performing an absolute measurement of $\overline{D}_i$.

2) The determination of the absorbed dose to the medium, D_m, at the point P, in the absence of the detector, by a calculation based on the knowledge of $\overline{D}_i$.

In the case of an ionization chamber the absorbed dose to the medium, D_m, can be calculated from the mean absorbed dose in the detector, $\overline{D}_i$, by the well-known Bragg-Gray relation.

$$D_m = \overline{D}_i \left(\frac{\bar{S}}{\rho}\right)_{m,i} \qquad (1)$$

where $\left(\frac{\bar{S}}{\rho}\right)_{m,i}$ is the weighted mean ratio of the collision stopping power of the medium, m, to that of the detector material, i. Equation (1) can be used for both photon and electron beams with energies above 1 MeV for a sufficiently small detector.

The procedure in the Nordic protocol

In view of their simplicity and precision, the method of using air ionization chambers is recommended in the new Nordic protocol.

The modified Bragg-Gray equation (2) is recommended for the determination of the absorbed dose, D_w, at the reference point in the water in the absence of the chamber at the users radiation quality. In the case of a cylindric chamber this gives the absorbed dose at the position of the centre of the ionization chamber.

Thus
$$D_w = \overline{D_{air}} \cdot p_u \, s_{(w,air)u} \qquad (2)$$

where
$$\overline{D_{air}} = N_D \cdot M_u \qquad (3)$$

and

$\overline{D_{air}}$ = mean absorbed dose to air in the cavity of the ionization chamber measured in water at the users radiation quality in Gy.

$s_{(w,air)u}$ = mass stopping power ratio, water to air, at the reference point at the users radiation quality.

p_u = total perturbation factor including corrections for
- lack of water equivalence in the ionization chamber material at the users radiation quality
- perturbation of the fluence due to the insertion of the air cavity
- location of the effective point of measurement of the cylindric chamber due to the curved ionization chamber wall.

N_D = absorbed dose to air ionization chamber calibration factor in Gy per nC or Gy per div.

M_u = meter reading at users quality corrected for temperature, pressure, recombination, etc., in nC or div.

Equation (2) can be used for both electron and photon beams.

Calibration of the ionization chamber

A calibrated ionization chamber must be used for the determination of the absorbed dose to water, D_w. The chamber in use shall be calibrated at standards laboratories in a beam of ^{60}Co γ-rays. The calibration factor for the chamber, N_D, can be evaluated from a known exposure in free air, X_{air}, or from observed air kerma, K_{air}. The following equations will give the relation between N_D, X_{air} and K_{air}.

$$N_D = \frac{X_{air} \cdot \frac{\bar{W}}{e} \cdot k_{att} \cdot k_m}{M_c} \qquad (4)$$

and

$$N_D = \frac{K_{air} (1 - g) \cdot k_{att} \cdot k_m}{M_c} \qquad (5)$$

where

$\frac{\bar{W}}{e}$ = mean energy expended in air per ion pair formed and per electron charge (W/e is equal to 33.85 J C^{-1})

k_{att} = attenuation and scattering in the ionization chamber material at the calibration in the ^{60}Co- γ beam.

k_m = chamber material dependent factor correcting for the lack of air equivalence of the ionization chamber material.

g = fraction of the energy of the secondary charge particles lost to bremsstrahlung in air (g is at ^{60}Co-γ beam close to 0.004).

M_c = meter reading at calibration corrected for temperature, pressure etc. in nC or div.

Values of the factors k_{att} and k_m for typical cylindrical chambers are given by Johansson et al (1977). For a Farmer 0.6 cc chamber with walls of graphite or similar materials and with a perspex build-up cap the k_m times k_{att} for a ^{60}Co-γ beam is equal to 0.974.

The total perturbation factor, p_u

The total perturbation factor is introduced in the modified Bragg-Gray equation (2) to correct for the disturbance of the particle fluence caused by the insertion of the ionization chamber. The value of the correction factor depends on the ionization chamber size and construction and on the radiation beam quality.

The total perturbation factor include corrections for three different effects, namely:

1) a correction for the lack of water equivalence of the ionization chamber material. This will disturb the electron fluence in the air cavity, as some of the electrons then will be produced in a non-water equivalent material. This effect depends on the material and thickness of the chamber wall and varies with radiation beam quality.

2) a correction for the different scattering properties of the water and the chamber (wall and air). For electron beams this correction could be up to several per cent. This effect depends on the size and geometry of the chamber and varies with electron energy.

3) in the case of a cylindric chamber a correction for "the effective point of measurement" due to the curved ionization chamber wall. For absorbed dose measurements at the reference point a correction factor should be applied to the reading. The centre of the cylindric chamber shall then be placed at the depth of the reference point.

Total perturbation factors for cylindric ionization chambers with a diameter of 5 mm have been given by Johansson et coll. (1977).

The mass stopping power ratio, $(s_{w,air})_u$

The use of the modified Bragg-Gray equation (2) requires an accurate knowledge of the stopping power ratio $(s_{w,air})_u$. For electron radiation the stopping power ratios from Berger et coll. (1975) are recommended and for photon radiation those from the ICRU (1969, Table A3).

Two different sets of stopping power ratios should strictly have been used, one for a chamber of air equivalent walls and another for a chamber of water equivalent walls. However, in electron beams the two sets of data differ with less than one per cent. For most practical purposes this small difference can be ignored. Therefore, for simplicity, only one set of $(s_{w,air})_u$ is recommended.

Measuring procedures

For photon beams with maximum energies above 1 MeV and electron beams with energies above 10 MeV, the absorbed dose at the reference point should be determined in a water-filled phantom. The ionization chamber should be protected during the water measurement by a tube manufactured from polymethylmethacrylate. The tube should be attached to a holder that can be adjusted for measurements at various depths. The symmetry axis of the chamber must be positioned at the reference point.

For electron energies in the range 1 MeV to 10 MeV the absorbed dose in the reference point should be measured in a solid phantom. A plane parallel ionization chamber should then be used.

Conclusion and consistency

The here presented procedure will be introduced in the Nordic countries. Differences in the absorbed dose determination using the methods given in NACP (1972) compared to methods given in the new protocol can be as large as 3 to 4 per cent in extreme cases. Such cases are electron beams with energies from 1 MeV to 10 MeV, where now a plane parallel chamber is recommended.

In table 1 is shown the total conversion factor in Gy per R to be applied to the meter reading for a Farmer ionization chamber with walls of graphite or air equivalent walls. The chamber has been calibrated in a ^{60}Co-γ beam with a perspex build-up cap in free air. The calibration factor in R/nC or R/div have been used. For photon beams with energies above 4 MV the new NACP (1980) have conversion factors which are 2-3 per cent higher than the old factors for the type of chamber mentioned above. This

is what could be expected and is in good agreement with other investigations. Almond and Svensson (1977) and Nahum and Greening (1976). For electron beams there is a good agreement for energies above 10 MeV between the new and old conversion factors.

Total conversion factor (Gy/R)

Radiation quality	Depth mm	NACP 1980 1)	NACP 1972	ICRU 1969	ICRU 1972 2)
^{60}Co γ -ray	50	0.00949	0.0095	0.0095	
8 MV X-ray	50	0.00946	0.0093	0.0093	
20 MV X-ray	100	0.00926	0.0091	0.0090	
30 MV X-ray	100	0.00918	0.0090	0.0089	
$\bar{E}_o$ = 10 MeV e^-	20	0.00873	0.0089		0.0088
$\bar{E}_o$ = 20 MeV e^-	30	0.00843	0.0085		0.0084
$\bar{E}_o$ - 30 MeV e^-	30	0.00817	0.0082		0.0082

$\bar{E}_o$ - The mean energy of the electron beam at the surface of the phantom.

1) The factor is equal to $k_{att} \cdot k_m \cdot \frac{W}{e} \cdot k_l \cdot s_{w,a} \cdot p_u$ see eq (2), (3) and (4) for a Farmer 0.6 cc ionization chamber with wall of graphite.

2) Correction for perturbation is made.

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HIGH ENERGY RADIATION DOSIMETRY AND CAVITY THEORY
A re-examination

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Abstract

High energy dosimetry by a solid or partly solid cavity of material different from the medium, either by an ionisation chamber and applying the C_λ and C_E concept, or by LiF, has in general been carried out at varying radiation energies with the cavity or wall material and its thickness virtually ignored. This approach which entails the application of Bragg-Gray relation and not an appropriate cavity expression cannot be right. C_λ and C_E data obtained by a limited semi-empirical expression which takes full account of chamber wall material and thickness are compared with C_λ and C_E data by the only other approach in the literature (Nahum and Greening 1978) which takes account of wall material and thickness. Recommended ICRU values (1969, 1972) are also presented for obvious reasons.

A similar parameter, the LiF response to high energy radiation relative to ^{60}Co photons as estimated by the semi-empirical approach, is also compared with existing theoretical data and normalised $FeSO_4$ estimates.

(1) Introduction

The concept leading to the introduction of C_λ and C_E, was proposed by Greene and Massey (1966); these two parameters are of considerable importance in high energy dosimetry and are generally in use. However, their values as recommended by the ICRU (1966, 1972) are today not generally accepted, (Nahum and Greening 1976). Fregene (1977a) argued that a shortcoming of previous analyses including that of the ICRU, is that both the chamber wall, and its lining of material different from the medium are ignored in their derivation; the need to allow for the wall by a suitable cavity theory was stressed. As an alternative, Fregene proposed that chambers may be constructed such that the wall and lining are the same or equivalent to the medium (a wall-less cavity situation). Greene and Massey (1978), Pitchford and Bidmead (1978) etc. have agreed in principle that the wall effect mentioned in Fregene (1977a) should be taken account of.

(2) The parameters C_λ and C_E - conversion factors of dose in roentgens in air to absorbed dose in rads in water have the unit rads per roentgen. The values of C_λ or C_E at a particular high energy are dependent on which of the following three approaches is assumed in the estimation of C_λ and C_E.

If we assume that dosimetry is by an ideal Bragg-Gray gas cavity, we have

$$C_\lambda \text{ or } C_E = \frac{W}{e} (S_{m,i})_{E \text{ or } \lambda} \quad \ldots\ldots\ldots\ldots (i)$$

as $\frac{W}{e}$, has the same units as C_λ and C_E, equation (i) is dimensionally balanced. It is not tied to ^{60}Co calibration.

If on the other hand we assume a finite sized wall-less gas cavity whose dimension at ^{60}Co energy is characterized by a displacement factor A, then

$$C_\lambda \text{ or } C_E = A.\frac{W}{e} (S_{m,i})_{E \text{ or } \lambda} \quad \ldots\ldots\ldots\ldots (ii)$$

The perturbation correction ($P_{E \text{ or} \lambda}$), following ICRU (1972) is taken as unity. The expression (ii) for C_E is the same as applied in ICRU recommended data: it is correct for a wall-less chamber but not a walled one. The expression for C_λ is also correct for the hypothetical wall-less gas chamber which at high radiation energies, with due correction for displacement, approximates a Bragg-Gray cavity at normal thimble sizes.

In practical measurements a walled cavity of material different from the medium is used, in this instance, neither equations (i)nor (ii) are applicable. In this case a limited semi-empirical expression based on linear principles of energy deposition along thin walls, which takes account of wall material and thickness (x) at energy E, such that the seondary electron range is r_o, may be applied.

$$C_\lambda \text{ or } C_E = A. \frac{W}{e} \left\{ \frac{1}{S_m^W} + \left(1 - \frac{1}{S_m^W}\right) \frac{x}{r_o} \right\} S_a^W \times P_{E \text{ or} \lambda} \quad \ldots\ldots (iii)$$

Although a walled chamber is used in practice, however in the application of C_λ and C_E values, the condition for a wall-less chamber i.e. equation (ii), the same as in ICRU (1972) estimation of C_E is used; the C_λ format also did not take account of the wall. Fig. (1) illustrates schematically the three situations above.

(3) Apart from the preliminary publications of C_λ and C_E data in Fregene (1977b) which were obtained by applying the limited semi-empirical cavity expression, the only other values of C_λ and C_E which take account of chamber wall and thickness are in Nahum and Greening (1978), who used a modified Spencer-Attix cavity theory. Their work provides an opportunity to compare C_λ and C_E data with those estimated by the semi-empirical expression which is valid for the typical standard chamber wall thickness in high energy beams. It should be noted that Burlin's (1966) general cavity theory is also a modification of the Spencer-Attix theory. While the photon beam component of Burlin's theory has been widely accepted, the electron beam component has been widely criticised Almond and McCray (1970), Paliwal and Almond (1975), Holt et al. (1975), Fregene (1976) and Shiragai (1977).

It is worth noting that in Nahum and Greening (1978), they took account of the chamber's wall material by a $(\frac{\mu_{en}}{\rho})$term which allowed for direct photon interactions with it. However, for electron beams in which no photon is present their expression should reduce in effect to that for a Bragg-Gray cavity or rather that of a wall-less cavity, identical to the ICRU approach. This is also reflected in the closeness of their C_E data with ICRU (1972) values for C_E, table (ii).

Tables (i) and (ii), show the values of C_λ and C_E as given by the semi-empirical expression, Nahum and Greening (1978), and ICRU (1969 and 1972). The ICRU C_λ data differ considerably from the other two, while the $C_E$data agree very well with Nahum and Greening's C_E.

Relative Response of LiF, a Cavity Effect

(4) A similar problem to that of the C_λ and C_E values, is the relative response of LiF to high energy radiation and ^{60}Co photons, this response has been analyzed on the basis of the semi-empirical approach which relates dose (D_x) in detector w, of thickness x, and dose (D_m) in medium m.by

$$\frac{D_x}{D_w} = \frac{1}{S_m^w} + \left(1 - \frac{1}{S_m^w}\right) \frac{x}{r_o} \quad \text{.....(iv)}$$

The relative response for LiF obtained by expression (iv)in table (iii), is in excellent agreement with the normalized comparative $FeSO_4$ experimental values as determined by different authors (Fregene 1977c). It would seem that for commonly used sizes of LiF, about 1 mm thick, a 7% decrease in LiF response to high energy radiation relative to ^{60}Co photons owing to the solid cavity nature of LiF occurs.

(5) In conclusion, it should be stated that dosimetry in general even by tiny detectors, if not completely matched to medium, should be based on an appropriate cavity expression; the common approximation of these situations by the Bragg-Gray relation is not precise.

A semi-empirical expression based on linear energy deposition by secondary electrons has produced data which not only confirm reliable experimental finding of response of LiF to high energy radiation relative to ^{60}Co photons but agrees quite well with Nahum and Greening's (1976, 1978) C_λ data; both of which differ appreciably from ICRU data. The revised C_E data by the semi-empirical approach differ slightly (over 1% below 10 MeV) from ICRU and Nahum and Greening's which oddly enough agree quite well.

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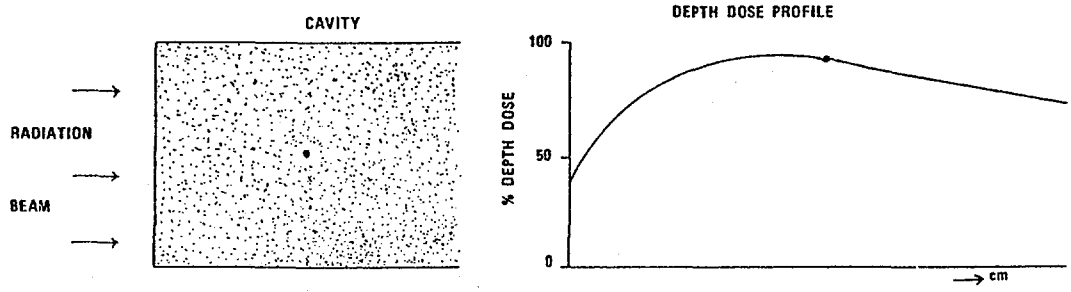
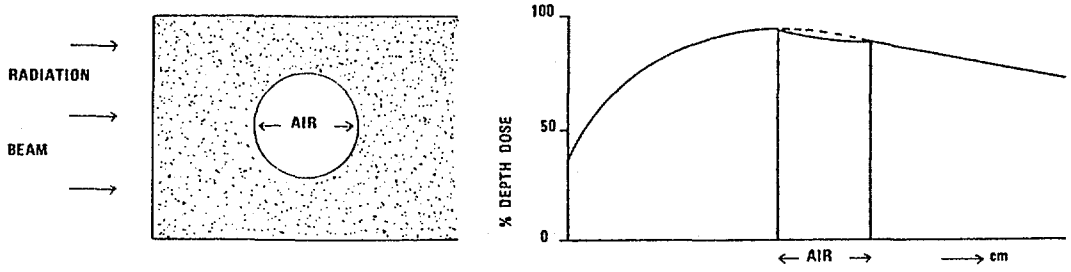
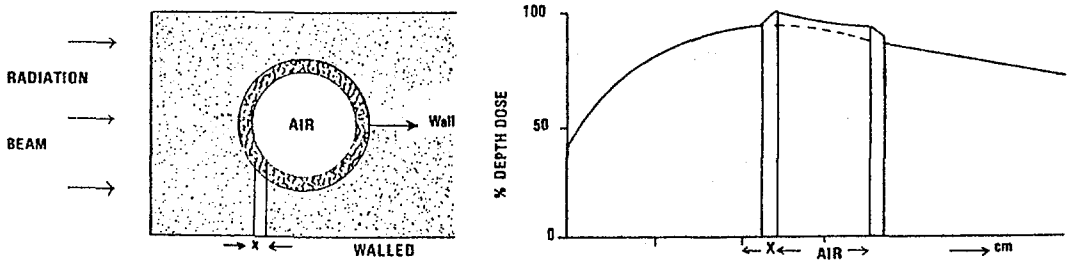


POINT CAVITY; BRAGG-GRAY CAVITY



WALL - LESS CAVITY – DISPLACEMENT FACTOR "A"



WALLED CAVITY-WALL THICKNESS (x); DISPLACEMENT FACTOR "A"

Comparison of Recent C_λ Values and ICRU Data

Photon Energy (MV)	Nahum and Greening (1978)	ICRU 1969	Semi-Empirical
2.0	.950	.950	.950
^{60}Co	.957	.950	
4		.94	
5			.959
6	.954	.94	
10		.93	.954
12		.92	
14	.939 (13MV)	.92	
15			.948
18		.91	
20	.936 (19MV)	.90	.942
25	.936 (26.8MV) .929 (26.8MV)	.90	
30	.921 (31MV)	.89	.928
35	.913 (31MV)	.88	.922
40			.919

Table (i)

Comparison of Recent C_E Values and ICRU Data

E_o Initial Energy Electrons	Nahum and Greening (1978)	ICRU 1972	Semi-Empirical
2			.933
5	.920	.922	.912
10	.890	.893	.883
15		.858	.852
20	.845	.848	.840
25		.830	.826
30	.815	.816	.815
35		.804	.802
40		.794	.795

C_E corrected to ICRU recommended depths by assuming a $2MeV/cm^{-1}$ energy loss with depth

Table (ii)

Comparison of Cavity Theories and $FeSO_4$ Data by LiF

Response to High Energy Radiation Relative to Co^{60} Photons

E L E C T R O N S							
NORMALISED $FeSO_4$			CAVITY THEORY VALUES				
No.	Author	Values	Burlin et al. 1969	Holt et al. 1975	Paliwal and Almond 1975	Shiragai 1977	Present Work
1.	Binks (1968)	.888 .917					
2.	Crosby et al. (1966)	.935					
3.	Pinkerton et al. (1966)	.916					
4.	Fregene (1976)	.945					
5.	*Bristovic et al. (1976)	.930					
6.	Almond & McCray (1970)	.938					
	Mean	.921	.69 - .85	.98 - 1.0	.905	.96 - .98	.935
P H O T O N S							
7.	*Bristovic et al. (1976)	.940					
8.	Almond & McCray (1970)	.930					
9.	Crosby et al. (1966)	.925					
	Mean	.932					.935

Mean of Ten Best $FeSO_4$ Values (Photons and Electrons) = $.929 \pm .014$

*Used a Chemical Dosimeter (although not $FeSO_4$)

Table (iii)

ANNEX

Procedures in External Radiation Therapy Dosimetry with Electron and Photon Beams with Maximum Energies Between 1 and 50 MeV

Recommendations by
the Nordic Association of Clinical Physics (NACP)

These recommendations have been produced by the Swedish Association of Radiation Physics and the Nordic Association of Clinical Physics aided by a large number of their members. The members of the Topic Group were H. Svensson (chairman), L. Lindborg (secretary), K. A. Johansson and N. Ulsø. Valuable criticism and aid is gratefully acknowledged: P. Almond, A. Brahme, J. Flatby, D. Harder, O. Mattsson, I. Uotila, and the Ph.D. students and teachers from the Radiation Physics Department in Linköping.

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Introduction

The International Commission on Radiation Units and Measurements (ICRU) has published general recommendations on dosimetry procedures for photons (ICRU 1969) and for electrons (ICRU 1972). These should preferably be supplemented by national or regional suggestions covering practical details of routine dosimetry procedures and taking into account the particular requirements and provisions of the country and region. Local recommendations have been prepared for the United Kingdom (HPA 1969, 1971, 1975), the USA (SCRAD 1966, 1971, AAPM 1975), West Germany (DIN 6809 1976, DIN 6800 1975 a, b) and the Nordic countries (NACP 1972).

The present report contains a revised Nordic protocol. Several reasons have motivated this revision. After publication of the first protocol several reports have been published giving new data on various effects which can change the factors used with ionization chamber dosimetry. The SI-units for the radiologic quantities should be applied. Another important reason is that the former Nordic recommendations were mainly based on investigations with betatrons, while within the Nordic countries now several other kinds of accelerators are used (standing wave and travelling wave linear accelerators and microtrons) with usually different properties, which have to be considered. Improved concepts for stating beam quality and beam uniformity etc are therefore introduced in the present report. Similar revisions are being carried out by the ICRU and the AAPM.

Differences in the absorbed dose determination using the methods given in NACP (1972) compared to methods given in the present protocol can be as large as 5 per cent in extreme cases. It is recommended that the new protocol will be adapted at various centres as soon as new calibrations of ionization chambers have been achieved.

In the present report *shall* means compulsory for compliance with this report and *should* means strongly recommended.

These recommendations do not include the complete procedures for dosimetry of electron beams in the range of 1 to 10 MeV mean electron energy at the phantom surface where plane-parallel chambers shall be used. Such procedures will be explained in a supplement to this protocol to be published in the near future.

The aim of the recommendations is to give hospital physicists a 'code of practice' to be followed at radiation therapy centres in Denmark, Finland, Iceland, Norway and Sweden so as to secure uniformity in dosimetry procedures. They cover the tests and measurements both when dosimetry is first performed with a new therapy apparatus and in the continuous supervision necessary to ensure that the dosimetry is properly employed in radiation therapy. In weighting high accuracy and theoretic strictness against practical usefulness, the latter has been given more emphasis so that the procedures may be performed easily at all therapy centres.

Principal features. The dosimetric method of using air ionization chambers is still recommended for linking the national standard to the local reference, mainly in view of their general availability, simplicity and precision. For the radiation quantities of concern here the ionization chambers shall be calibrated at national radiation standards laboratories in ^{60}Co-γ ray beams.

Since the formerly used C_E- and C_λ-values were only valid for air equivalent and water equivalent chamber walls, respectively, a new procedure for the determination of absorbed dose is recommended. The procedure is based on a derived absorbed dose ionization chamber factor (N_D) giving the ratio between the mean absorbed dose to air in the ionization chamber cavity and the scale reading. N_D is derived from a calibration in air in a ^{60}Co-γ ray beam. The absorbed dose to water at various radiation qualities is then obtained as the product of meter readings, N_D, stopping power ratios and perturbation factors. Stopping power ratios and perturbation factors are both listed. The latter are given for chambers of either air or water equivalent materials, the equivalence of concern being the property of generating secondary electrons. Water or air equivalent materials are recommended for the ionization chambers at least for reference instruments.

Table 1

Energy quantities for specifying radiation beams

Quantity	Use	Determination	Energy range
$E_{p,a}$	On accelerator console	$E_{p,a} \approx E_{p,0} + \Sigma S_{coll,i} \cdot \Delta X_i$ eq. (1)	1 MeV$\leq E_{p,a} \leq$50 MeV
$E_{p,0}$	Specification of absorbed dose distribution	$E_{p,0} = C_1 + C_2 R_p + C_3 R_p^2$ eq. (2) $C_1 = 0.22$ MeV $C_2 = 1.98$ MeV cm^{-1} $C_3 = 0.0025$ MeV cm^{-2}	1 MeV$\leq E_{p,0} \leq$50 MeV
$\bar{E}_0$	As reference to dosimetric constants	$\bar{E}_0 = C_4 R_{50}$ eq. (3) $C_4 = 2.33$ MeV $\cdot$ cm^{-1}	5 MeV$\leq \bar{E}_0 \leq$30 MeV

The increasing number of accelerators of different types and often quite different beam qualities necessitates a simple unified comparison of the quality of one beam with another. The main therapeutic and physical properties of the depth dose distribution of the beams are therefore characterized by new parameters not used in NACP (1972).

Energy determination at accelerators

A knowledge of the radiation quality is necessary because stopping power values and perturbation factors recommended here for ionization chamber dosimetry, are energy dependent and because standardized depth dose tables may be used for accelerators similar in construction, provided the energy is determined in a uniform manner (SVENSSON & HETTINGER 1971, SVENSSON 1971). Furthermore, quality parameters may be desired for the comparison of one beam with another. Depending on the parameter of interest different energy quantities are recommended. For electron beams, it is recommended to use a therapeutic range to describe the radiation quality in irradiation procedures.

Electron beams

Energy quantities. The intrinsic accelerator beam, i.e. the electron beam just before the exit window of the accelerator but after beam handling magnets and energy defining slits, has a certain energy distribution. This can be characterized by its maximum energy ($E_{m,a}$), its most probable energy $E_{p,a}$, its mean energy $\bar{E}_a$, and its energy spread Γ_a; the index a stands for accelerator. As the beam passes through the exit window and different materials from the exit window to the phantom surface the energy will decrease and the energy spread increase. Therefore, analogous energy quantities can be defined for the phantom surface, index o, and for any depth z in the phantom, index z. These different electron energy quantities are recommended and are summarized in Table 1 and Fig. 1. Their principal uses are:

$E_{p,a}$ (the most probable energy in front of the accelerator window): For a given accelerator beam setting different beam scattering foils or decelerators are often used. However, the energy instruments are usually constructed to give a measure of the electron energy of the intrinsic beam. Therefore, it is recommended that the energy indication meter and the energy selection setting on the console desk be calibrated in an energy quantity which is independent of the materials in the beam. $E_{p,a}$ should be the energy quantity to use for this purpose.

$E_{p,0}$ (the most probable energy at the phantom surface): To indicate the energy of an absorbed dose distribution, $E_{p,0}$ shall be used. The reason is that this energy quantity is well related to the practical range, R_p, which generally is used for energy determination. $E_{p,0}$ is in most accelerator facilities 1 to 2 MeV lower than $E_{p,a}$ for energies below some 20 MeV. This difference may increase with energy.

$\bar{E}_0$ (the mean energy at the phantom surface): In absorbed dose measurements with an ionization chamber the relevant stopping power ratios and perturbation factors must be known. These are in this protocol given as a function of $\bar{E}_0$ and the depth of the chamber in the phantom (Tables 5, 7). [In NACP (1972) the absorbed dose conversion factors (C_E) were correlated to the mean energy at a phantom depth, a quantity estimated from the relation

$$\bar{E}_z \approx E_0 (1 - \frac{z}{R_p}).$$

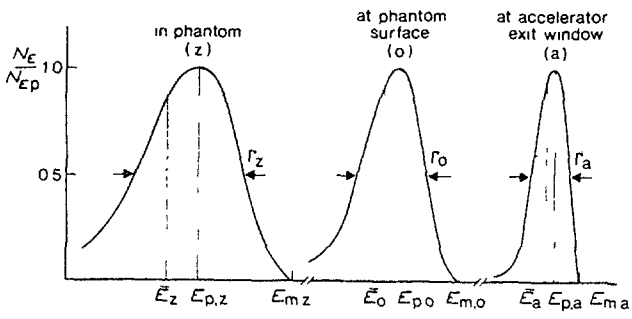

Fig. 1. The distribution of electrons in energy in front of the accelerator window (a), at the phantom surface (o), and at the phantom depth (z). The ordinate shows the differential distribution in energy of the one directional plane fluence, N_E, normalized to its value at the most probable energy, N_{Ep}.

In this equation E_0 was approximated by $E_{p,0}$. In the present protocol it is considered that $\bar{E}_0$ may be a few MeV lower than $E_{p,0}$ and therefore, that a determination of $\bar{E}_0$ should be made.]

Energy determinations. $E_{p,0}$ should be determined by analysing the central axis depth dose curve making use of the empirical relation between the practical range in water, R_p, and $E_{p,0}$ (Table 1). In the energy range 7 to 20 MeV eq. (2) gives, within ±1 per cent, the same $E_{p,0}$ as the linear equation recommended in NACP (1972), i.e. $R_p = E_{p,0} \cdot 0.52 - 0.3$. Outside this range the difference increases. For the energy range 1 to 50 MeV the relation recommended here (eq. 2) fits experimental (MARKUS 1964, HARDER & SCHULZ 1971) and calculated data (SELTZER et coll. 1977) to within 2 per cent.

The practical range, R_p, in eq. (2) (Table 1) is defined as the intersection depth of the tangent through the steepest point (inflection point) of either a depth absorbed dose curve or a depth ionization curve and the photon background (Fig. 2). The curves should be measured as described on page 17 making use of the concept of the effective point of measurement.

Depth absorbed dose and depth ionization curves in a water phantom give within about 1 to 2 mm the same value of R_p (SVENSSON & HETTINGER 1971). For the determination of $E_{p,0}$ the measurement of depth ionization curves is recommended. Above 10 MeV both cylindric and plane-parallel chambers could be used but below about 10 MeV only plane-parallel chambers should be used as they have the best defined effective point of measurement. For energies above 10 MeV a water phantom shall be used, while below 10 MeV either a water or a plastic phantom can be used. Large field sizes must be

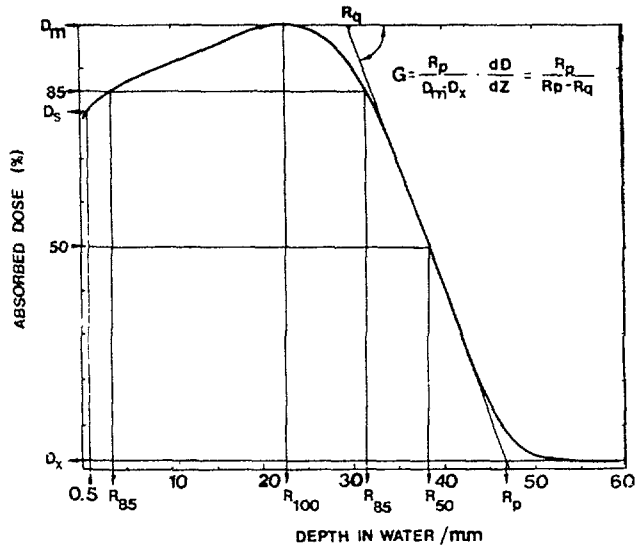

Fig. 2. The depth absorbed dose distribution with definitions of the parameters used in the text. D_m is the level of maximum absorbed dose, D_s is the surface dose measured at 0.5 mm depth, D_x is the photon background, G is the dose gradient, R_{100} is the depth of dose maximum, R_{85} is the therapeutic range, R_{50} is the half-value depth, and R_p the practical range. (From BRAHME & SVENSSON 1979.)

used, i.e. ≥120 mm × 120 mm for energies up to 20 MeV and ≥200 mm × 200 mm above that energy. The source–surface distance (SSD) should be ≥1 m. With some plastic phantoms the relation between R_p in water and in plastic may be calculated from the formula (MARKUS 1961, DIN 1976).

$$\frac{R_{p,H_2O}}{R_{p,pl}} = \frac{\varrho_{pl}}{\varrho_{H_2O}} \times \frac{\left(\frac{Z}{A}\right)_{eff,pl}}{\left(\frac{Z}{A}\right)_{eff,H_2O}} = k \qquad (4)$$

In this equation $(Z/A)_{eff} = \Sigma f_i (Z_i/A_i)$, where f_i is the fraction by weight of the constituent element of atomic number Z_i and the relative atomic mass A_i. ϱ is the density. Index pl stands for plastic. Eq. (4) may be used for materials with $(Z^2/A)_{eff} < 4$ (DIN, 1976); values of some materials are given in Table 2.

$\bar{E}_0$ should be determined from the empirical eq. (3) (Table 1) relating it to the half value depth, R_{50}, defined as the depth of the 50 per cent depth absorbed dose in a water phantom (Fig. 2). The linear eq. (3) should be used in the energy range 5 to 30 MeV. The relation between R_{50} and $\bar{E}_0$ outside this range should be taken from Table 5 and Fig. 3. Eq. (3) is strictly valid only for an infinite SSD but may also be used for SSD down to 1 m for energies up to approximately 20 MeV (Fig. 3).

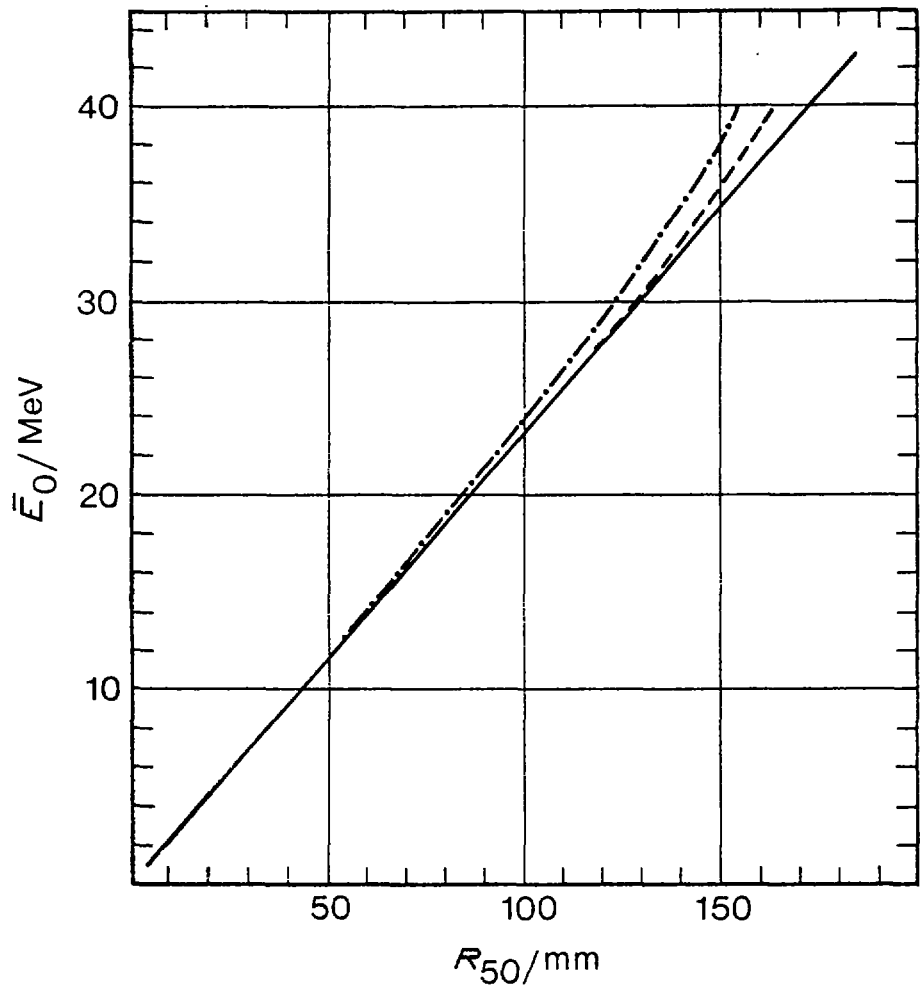

Fig. 3. The relation between R_{50} and $\bar{E}_0$ for large field sizes. The solid line is valid for R_{50} determined from beam axis depth absorbed dose curves with SSD=∞, the broken line for beam axis depth absorbed dose curves with SSD=1 m, and the dash-dotted line for beam axis depth ionization curves with SSD=1 m.

Table 2
Some characteristics of phantom materials

Phantom material	Composition	ϱ g·cm^{-3}	$\left(\frac{Z}{A}\right)_{eff}$	k
Water	H_2O	1	0.555	1.000
Polystyrene	C_8H_8	1.05	0.538	1.018
Perspex	$C_5H_8O_2$	1.18	0.540	1.148
A 150	see ICRU (1977)	1.12	0.548	1.106

Above that energy inverse square law corrections should be performed. R_{50} should be measured with large field sizes and should be determined from a depth absorbed dose curve but may be evaluated from a depth ionization curve and the graph in Fig. 3.

$E_{p,a}$ should be calculated according to eq. (1) in Table 1. The calculation means that the energy losses of the electrons in all scattering materials in the radiation beam, e.g. window, scattering foils, transmission chambers and air, must be added to the electron energy, $E_{p,0}$. The thickness of the various materials, ΔX_i, which the beam passes from the inner side of the tube window to the phantom surface must be known as well as the collision stopping power of each material $s_{coll,i}$. Materials in the beam very near the phantom surface should, if possible, be removed in the measurements of $E_{p,0}$ as eq. (1) gives an incorrect estimate of $E_{p,a}$ with materials near the phantom surface.

Photon beams

Energy determinations. For a proper choice of stopping power ratios and perturbation factors in photon beams a measure of the photon beam quality can be estimated from depth ionization measure-

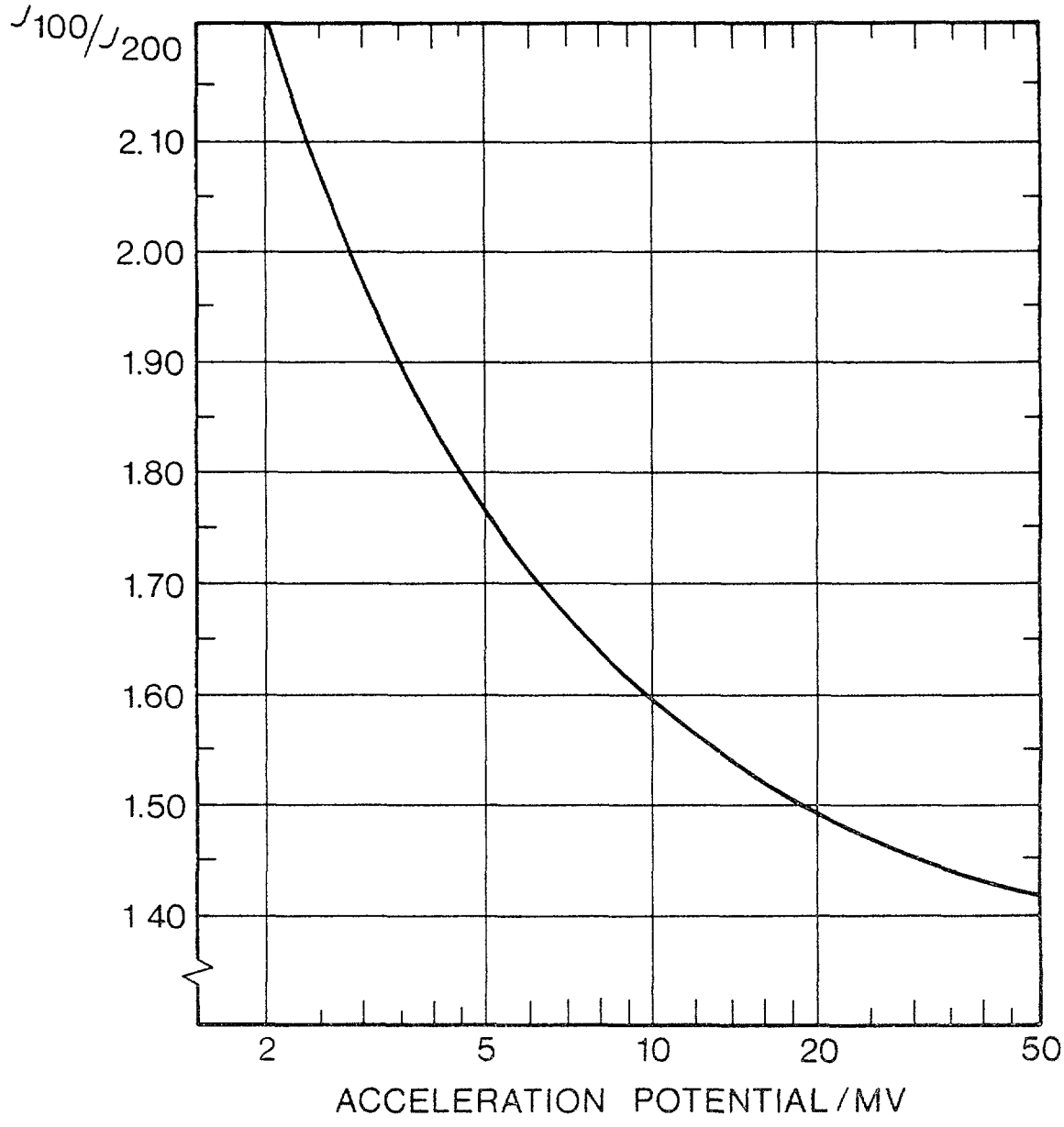

Fig 4 The ratio J_{100}/J_{200} ($\approx D_{100}/D_{200}$) as a function of the accelerating potential (or $h\nu_m$) is shown for a SSD=1 m and a field size of 100 mm × 100 mm For accelerators with the same accelerating potential the ratios differ from beams with different targets and flattening filters and are as a rule smaller for betatrons than for linear accelerators and microtrons All ratios over 20 MV are from betatrons, while those below 20 MV are taken from linear accelerators J_{100}/J_{500} is recommended as input data for $(s_{w,air})_Q$

ments (BRAHME & SVENSSON 1979) The ionization at the depth of 100 mm and 200 mm in a water phantom is measured for a field size of 100 mm × 100 mm and an SSD of 1 m and the ratio J_{100}/J_{200} determined The ratio is stronger related to the mean photon energy than the maximum photon energy Therefore, if the ratio is calculated from published data and plotted against the maximum photon energy, a rather large spread is found (Fig 4) The J_{100}/J_{200} method is recommended for estimation of the photon beam quality rather than measurements of the half value depth, R_{50}, as the values of R_{50} depend upon the contamination of electrons in the peak absorbed dose of the photon depth dose curve

The maximum photon energy, $h\nu_m$, in the photon beam can be estimated with two different methods When both photon and electron beams are available from the same accelerator the maximum photon energy may, within 1 or 2 MeV, be approximated by $E_{p,a}$ The energy meter on the accelerator is usually

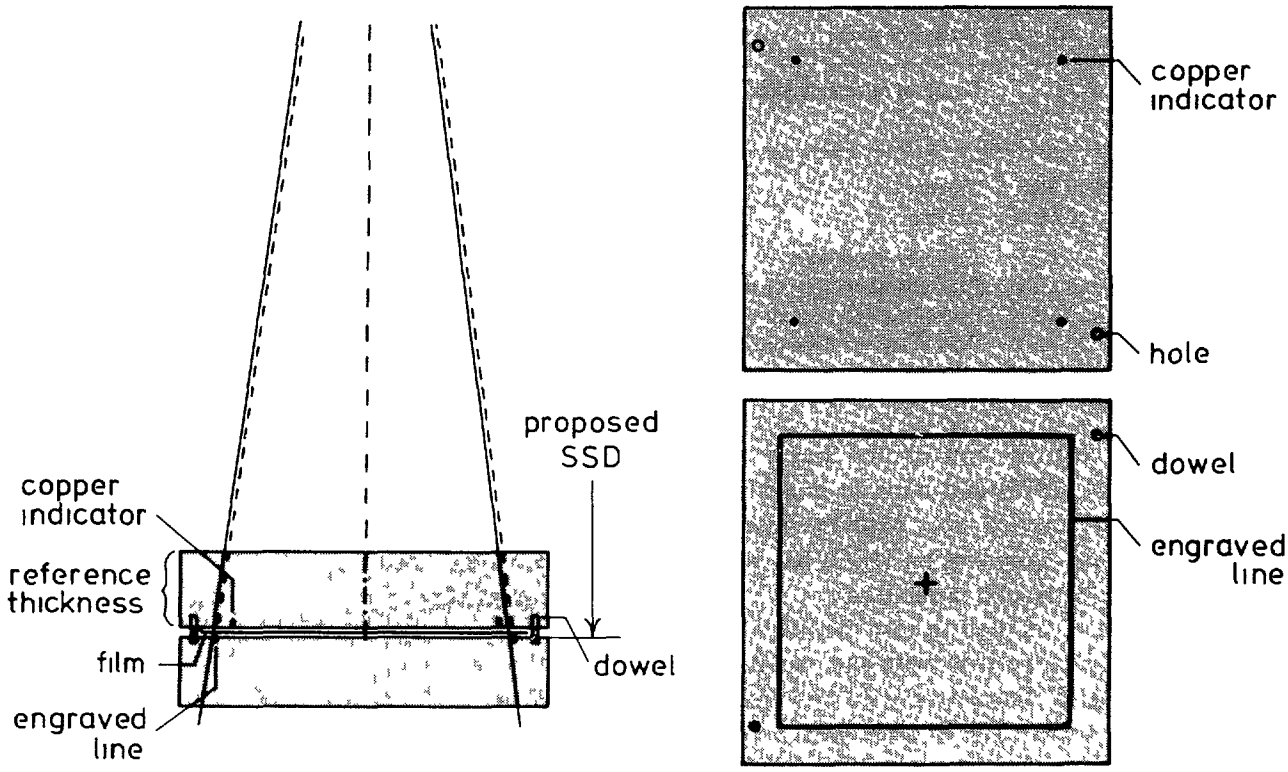

Fig 5 Polystyrene phantom to be used for beam alignment check A small misalignement is indicated in the figure as the solid and broken lines do not coincide --- Light beam — Radiation beam ·—· Beam axis

designed to give a measure of the electron energy before the exit window and photon target. The meter can therefore be calibrated against $E_{p\,a}$ for the electron beams (see page 5). Alternatively a method based on (γ, n) threshold measurements may be used (NACP 1972). This method makes a direct calibration of the energy instrument in the maximum photon energy, $h\nu_m$, possible. The maximum photon energy has conventionally been used to specify depth dose distributions.

Recent investigations have shown that the shape of the depth absorbed dose curves and the mean energy for photon beams may be more dependent on the construction of target and flattening filter than on a change of a few megavolts in accelerating potential, i.e. in change of $E_{m\,a}$ (PODGORSAK et coll. 1975, NAHUM 1978). Therefore, it is not considered necessary to carry out determinations of $h\nu_m$, using the methods mentioned, neither for the purpose of dosimetry nor for the specification of depth absorbed dose curves. The J_{100}/J_{200} method is uncertain for the estimate of the maximum photon beam energy, but is well related to the mean photon energy and should therefore be used for dosimetric procedures. The ionization ratio is recommended as a beam quality parameter for use in choosing the stopping power ratios necessary for ionization chamber dosimetry (Table 6).

Geometric considerations

The position of the radiation beam must be defined and indicated to be able to perform accurate radiation therapy. In this section some simple procedures are given. The discussions are limited to rectangular unmodified beams only, e.g. without wedges or blocks.

Beam alignment

The beam alignment shall be checked on the installation of a new therapy unit. The manufacturer should be held responsible for any adjustment required before the accelerator is handed over for routine treatments.

The proper alignment of the different types of beam axes (collimator rotation axis, geometric beam axis, radiation beam axis, and light beam axis as defined in the Appendix) shall be checked before the absorbed dose distributions are determined. Practical beam alignment procedures have been detailed in

Table 3
Depth of reference plane

Type of radiation	$h\nu_m$ or E_{p0}	Depth of reference plane
Photons	1–<10 MeV	50 mm
	10– 50 MeV	100 mm
Electrons	1– <5 MeV	Peak absorbed dose
	5–<10 MeV	Peak absorbed dose or min 10 mm
	10–<20 MeV	Peak absorbed dose or min 20 mm
	20– 50 MeV	Peak absorbed dose or min 30 mm

the case of electron and photon beams by HPA (1970), AAPM (1975) and may be consulted when the checks are carried out. Also the International Electrotechnical Commission (IEC) has a working group dealing with such procedures.

An alternative method to test the position of the light beam in comparison with the radiation beam appears in Fig. 5. The test should be carried out in the following order. The bottom sheet of the phantom is placed perpendicular to the collimator axis with the front surface at the SSD in use. The light beam size and position shall coincide with the engraved line on the bottom sheet. The numerical field size shall be noted. A film in a light tight cover is placed on the bottom block and a top block with 4 metal indicators is placed with care on the film without moving the bottom block. The thickness of the top block should be approximately equal to the reference depth (Table 3). After irradiation 4 dots on the film are observed from the indicators. These dots should be used for comparison of the position of light and radiation beam. The uniformity index, the radiation field size and the physical penumbra may also be determined from the same film. The beam and the collimator axes shall agree within 2 mm and the position and size of the radiation beam and light beam shall agree within 2 mm at an SSD of about 1 m.

Depth of the reference plane

Recommended depths for the reference plane for various radiation qualities are given in Table 3. For electron beams the depth of the absorbed dose maximum is recommended as the reference plane, instead of a fixed depth due to the peaked depth absorbed dose curves for some low energy electron beams. However, for some accelerators and beam sizes the maximum absorbed dose can occur at very small depths due to electrons scattered from, for instance, collimators. In those cases the depth of the reference plane should be taken as the minimum values given in Table 3.

Uniformity of the beam

A useful measure of the beam uniformity is the uniformity index (see Appendix). This index should exceed 0.80 in the reference plane for the absorbed dose at field sizes larger than 100 mm × 100 mm for both photon and electron beams. In addition, the beam uniformity should be such that the absorbed dose at any point in the reference plane should not exceed 103 per cent of that at the reference point. For accelerator beams the physical penumbra (see Appendix) shall not exceed 8 mm at an SSD of about 1 m. Some accelerators are overflattened at small phantom depths in order to achieve a good uniformity index at large depths. Then for any plane parallel to the reference plane the absorbed dose of any arbitrary point in that plane should not exceed 107 per cent of its value on the beam axis.

The radiation beams should as minimum requirements fulfil the values given but each hospital physicist should work for achieving as good beam uniformity as possible generally aiming at an absorbed dose variation within the target volume of less than ±5 per cent (ICRU 1976).

The uniformity, the radiation field size and the physical penumbra may be measured in various ways. Photographic film in a polystyrene phantom offers the advantages of high spatial resolution, simplicity of handling, short irradiation times and above all the fact that it will lead to simultaneous recording of the entire radiation field. With some care, the figures given for absorbed dose uniformity may be equated to the same figures obtained for net film blackening. A disadvantage of the film method is, however, that it is best used with an automatic or semi-automatic density plotter. With the film method the beam uniformity should be investigated by means of photographic film in a light tight cover of regular thickness but not of a radiation fluorescent material; industrially pre-wrapped film may be used. The film should be exposed in a polystyrene phantom (Fig. 5) and the absorbed dose should be about 1 to 2 Gy (a typical treatment absorbed dose) so as to minimize the influence of initial perturbations in accelerator beams and of shutter movement in ^{60}Co-γ beams. Before irradiation, accelerators should have been run under operating conditions for

a sufficient period of time to effect a proper warm-up. The relation between film blackening and the absorbed dose depends critically on the development procedure used; parameters of importance are type of film and developer, development time and temperature. All these should be combined to produce a linear relationship between blackening and absorbed dose over a large range. The aperture diameter of the density reader should be selected to exert negligible influence on the spatial pattern recorded. The variation in film density on a homogeneously exposed film should be less than ±2 per cent; only a few types of film seem to meet these requirements (RASSOW et coll. 1969, DUTREIX 1976). The film density versus absorbed dose should be checked regularly and at least every time a film batch or developer is changed.

Alternatively a semi-conductor detector or a small ionization chamber (i.e. diameter of not more than 5 mm) could be used for traversing the beam in the reference plane in a water tank for gantry angles at 90°, 270° and possibly 0° from the vertical position. This method will produce higher precision than the film method, provided that in connection with accelerators, a monitor probe is used to correct for output fluctuations. The monitor probe should be placed either outside the region of interest (the 50 per cent isodose curve) or in the centre of the beam, in which case the shadowing effect must be taken into account when evaluating the results. For other gantry angles the beam could be investigated by means of a polystyrene block with holes for the detector (NAYLOR & CHIVERALLS 1970). The absorbed dose distribution in the reference plane may then be equated to the ionization current distribution.

Determination of absorbed dose at reference points

The absorbed dose determination shall be made by air ionization chamber measurements performed by a qualified person. A new determination shall be made when new conditions of irradiation are employed. The determination shall be confirmed with an independent dosimetric method for instance calorimetry or ferrous-sulphate dosimetry and even less accurate methods such as those based on solid state dosimetry may be used. Both the absorbed dose determination and confirmation shall be performed before irradiation of patients. In connection with these absorbed dose determinations a constancy check procedure shall be incorporated.

Ionization chambers and electrometers

Reference instrument. Each radiation therapy centre shall have at least one local reference (standard) ionization chamber, together with an electrometer selected as a reference instrument for calibration of field ionization chambers and other dosemeters. A reference chamber may also be used for the first calibration of a new therapy machine. However, due to good stability of modern electrometers a reference electrometer may be used also for other purposes. The reference chambers shall be calibrated at a standardizing laboratory particularly for ^{60}Co-γ rays in air. The reference electrometer shall also be calibrated at a standardizing laboratory. The calibration is preferably carried out separately for the ionization chamber and the measuring assembly. The chamber should be re-calibrated at a standardizing laboratory at least once every 2 years. A longer interval can be acceptable for the electrometer, if its stability can be checked in an independent way.

The response of the reference instrument (ionization chamber and electrometer) should be checked at least quarterly against a suitable radioactive source at the radiation therapy centre, e.g. ^{60}Co-γ source (half-life 5.27±0.01 year). Any change in response of the reference instrument of more than 1 per cent revealed by the constancy checks should lead to a thorough investigation of instrument and subsequent re-calibration at the standardizing laboratory.

A cylindric chamber with an air volume of 100 to 1 000 mm^3 should be used as reference ionization chamber. If the chamber is to be used for calibrations of field instruments under conditions other than those at the standardizing laboratory (for instance in a phantom) it is essential that the air volume diameter in the chamber is between 4 and 6 mm and has a length of less than 25 mm. The wall of the chamber should be homogeneous graphite or tissue/water or air equivalent material. The thickness of the graphite chamber wall should preferably be about 0.5 mm as the perturbation factors reported here have been determined with this wall thickness (ALMOND & SVENSSON 1977, JOHANSSON et coll. 1977). The wall thickness is of less importance for water equivalent chambers. It is important that the material of the build-up cap is the same as that of the wall. In order to avoid mistakes the build-up cap

should be clearly marked and shall belong to a certain ionization chamber. The central electrode should be made of the same material as the wall and should preferably not be too massive. Leakage current, radiation-induced current and current generated in the stem must be negligible. The ratio between the ionization currents measured at positive and negative polarizing potential shall be checked and should be less than 1.005 for any radiation beam quality. This polarity effect increases with decreasing electron energy and should therefore for a cylindric ionization chamber be determined at various depths in a phantom for a beam of about 10 MeV mean electron energy at the surface.

Field instruments. The ionization chamber used for the assessment of absorbed dose must fulfil certain requirements. A cylindric ionization chamber should be used at all photon radiation qualities and at electron beams with a mean energy at the phantom surface, $\bar{E}_0$, above 10 MeV. A plane-parallel chamber should be used at electron energies, $\bar{E}_0$, equal to or less than 10 MeV. A supplement of this protocol will treat the measurement procedure used for the plane-parallel chamber.

The cylindric field chamber should have dimensions like the reference chamber. Chambers with unknown wall, central electrode material and thickness or with a thin layer of inner conducting material should be subjected to a special response test, i.e. be calibrated against the reference chamber for all radiation qualities used. Leakage current, radiation-induced current and current generated in the stem must be negligible.

The response of the field instrument should be checked at least quarterly against a suitable radioactive source or against the reference instrument. Any change in sensitivity of the field instrument of more than 1 per cent revealed by the constancy check should lead to a thorough investigation of the instrument and subsequent re-calibration against the reference instrument.

Ion recombination. The losses due to ion recombination are generally less than 1 per cent for continuous radiation or pulsed radiation of an absorbed dose to air in the chamber cavity per pulse of 1 mGy or less if the collection voltage is higher than 300 V for the type of chamber mentioned above. If the losses are less than 1 per cent, re-combination correction will not always be necessary. Correction for recombination losses can be made, either by calculation (BOAG 1966, ICRU 1964) or by measurements (ICRU 1972). For pulsed radiation beams the measured charge is plotted against the inverse of the polarizing voltage in the region of losses below 5 per cent. The released charge is determined by linear extrapolation in this plot to infinite polarizing voltage.

Electrometer. A precision low current measuring electrometer shall be used. The electrometer is usually based on a high gain amplifier with a low leakage current working either in a charge/voltage mode or in an integrating Townsend-balance mode. A digital display is usually preferable. A solid state electrometer may be built with either field effect transistors (MAUDERLY & BRUNO 1966) or by a varactor bridge input amplifier (JOHANSSON et coll. 1972). The scale on the electrometer should preferably be marked in coulomb and ampere. The electrometer should have a good long term stability over a number of years.

The instruments shall be constructed so as to minimize the effect of external electrostatic, magnetic and electromagnetic fields. However, the strong electromagnetic field that exists in and around some accelerators may affect the reading of the instrument. Special attention is needed to ensure that this does not occur. However, large mistakes in the dosimetry due to these effects will be discovered as 2 independent methods shall be used in absorbed dose determination at an accelerator.

Calibration at national standards laboratories

The local reference chamber and measuring assembly shall be calibrated at national standards laboratories in a beam of ^{60}Co-γ rays. The calibration of the ionization chamber shall be made in air at a distance of about 1 m from the source to the chamber centre and at a field size of about 100 mm × 100 mm. The cylindric chamber should have an additional cap of water or air equivalent material for chambers of water and air equivalent walls, respectively, to assure electron equilibrium. The total thickness of wall and additional material should be 0.45 ± 0.05 g cm^{-2}. If a perspex cap is used instead of the recommended materials and if this protocol is followed the systematic error introduced would be less than 1 per cent (ALMOND & SVENSSON 1977, JOHANSSON et coll. 1977).

International recommendations now exist for primary standards laboratories to derive air kerma from exposure measurements, using agreed upon conversion factors. The relation between air kerma (K_{air}) and exposure (X) is (ICRU 1971)

$$K_{air}(1-g)=X\bar{W}/e \quad (5)$$

where

g =the fraction of the energy of the secondary charged particles lost to bremsstrahlung in air (g is at ^{60}Co-γ rays close to 0.4 per cent, BOUTILLON 1977)

$\bar{W}/e$=mean energy expended in air per ion pair formed and per electron charge. ($\bar{W}/e$ is equal to 33.85 J · C^{-1}, ICRU (1979).)

The laborious use of the SI-units for exposure (C kg^{-1}) in some applications can then be overcome from the use of air kerma (unit Gy). The Nordic standards laboratories will be able to provide air kerma calibration factors (N_K) at ^{60}Co-γ beams defined by:

$$N_K=\frac{K_{air.c}}{M_c} \quad (6)$$

where

$K_{air.c}$=kerma in air at the centre of an ionization chamber in the absence of the chamber at the calibration radiation quality in Gy

M_c =meter reading at calibration corrected for temperature, pressure humdity etc. in C or div.

(General re-combination corrections should not be necessary to perform at the calibration in ^{60}Co-γ beams with the types of chambers recommended in this protocol.)

Derivation of absorbed dose ionization chamber factor

The mean absorbed dose to air, $\bar{D}_{air}$, inside the air cavity of the ionization chamber has to be evaluated from the observed air kerma, K_{air}, if, as suggested in this report, the Bragg-Gray relation is to be used for determination of absorbed dose to water. The following relation between $\bar{D}_{air.c}$ and $K_{air.c}$ is used:

$$\bar{D}_{air.c}=K_{air.c}(1-g)\cdot k_{att}\cdot k_m \quad (7)$$

where

k_{att}=attenuation and scattering factor, correcting for attenuation and scattering in the ionization chamber material at the calibration in the ^{60}Co-γ beam.

Table 4

k_{att} and k_m values for cylindric ionization chambers of sizes recommended in this protocol for different materials of the wall and cap combination. The values are expected to be dependent on the shape, size and electrode design

Chamber wall and cap material	k_{att}	k_m
Air equivalent	0.990	1.000
Graphite	0.990	0.991
Tissue equivalent (A 150)	0.990	0.963

k_m =chamber material dependent factor correcting for the lack of air equivalence of the ionization chamber material.

The correction factors k_{att} and k_m have been discussed extensively in the literature, recently e.g. by ALMOND & SVENSSON (1977) and JOHANSSON et coll. (1977).

The symbol A with various indices is often used instead of k_{att} and k_m; different authors giving different meaning to the symbol. The factors recommended (Table 4) are those given by JOHANSSON et coll. (1977).

The absorbed dose to air ionization chamber factor, N_D, is derived from eqs (6) and (7) as

$$N_D=\frac{\bar{D}_{air.c}}{M_c}=N_K(1-g)\,k_{att}\,k_m \quad (8)$$

N_D could be derived for any ionization chamber but the values in Table 4 are only valid for chambers described on p. 11. N_D could be stated by national standards laboratories or be calculated at the hospitals. If given by standards laboratories the factors k_{att} and k_m must be clearly stated in the protocol. (N_D is related to an exposure calibration factor (N_X) through the formula

$$N_D=N_X\,k_{att}\,k_m\frac{\bar{W}}{e}\,k_1 \quad (9)$$

where

k_1=1.00 with N_X in C kg^{-1} C^{-1}
k_1=2.58 10^{-4} with N_X in R C^{-1}.)

Absorbed dose determination at the reference point

For all photon radiation beams with maximum energies above 1 MeV and all electron radiation

Table 5

Recommended values of $(s_{w,air})_u$ and p_u for electron radiation at the reference point in a water phantom. The absorbed dose maximum is assumed to be at the minimum reference depths given in Table 3. The $(s_{w,air})_u$ shall be taken from Table 7 if dose maximum and therefore the reference point is situated at larger depths than given in Table 5. The p_u may be taken from Table 5 as it is not critically dependent on the depth

E_0 (MeV)	R_{50} (absorbed dose measurement) SSD=1 m mm	R_{50} (ionization measurement) SSD=1 m (mm)	Minimum reference depth (mm)	$(s_{w,air})_u$*	p_u**
1	3	3	2	1 144	-***
2	7	7	4	1 137	-
3	12	12	6	1 122	-
4	16	16	8	1 108	-
5	21	21	10	1 097	-
6	25	25	10	1 078	-
7	30	30	10	1 061	-
8	34	34	10	1 048	-
9	38	38	10	1 036	-
10	43	43	20	1 053	(0 975)
12	51	51	20	1 033	0 980
14	60	59	20	1 018	0 985
16	68	67	20	1 006	0 985
18	78	76	20	0 997	0 990
20	86	84	30	1 001	0 990
22	94	92	30	0 993	0 995
25	107	104	30	0 981	0 995
30	128	123	30	0 965	0 995
35	146	140	30	0 952	0 995
40	163	154	30	0 942	1 000
45			30	0 934	1 000
50			30	0 930	1 000

* Values from BERGER et coll. (1975) with cut off energy Δ= 15 keV

** Values from JOHANSSON et coll. (1977) for a cylindric ionization chamber with diameter 5 mm of tissue/water equivalent or air (graphite) equivalent material

*** A plane parallel ionization chamber is recommended for $E_0 \leq 10$ MeV

beams with $\bar{E}_0$ above 10 MeV, the absorbed dose at the reference point should be determined in a water-filled polymethylmethacrylate or polystyrene phantom with outer dimensions at least 0 3 m × 0.3 m × 0 3 m. The thickness of the phantom walls oriented towards the radiation source should be 5 mm or less. The water filling should be at least 0 25 m. If the distance between the edge of the beam and the edge of the phantom becomes less than 50 mm at the entrance surface, a larger water phantom should be used so that the distance will never be less than 50 mm. The ionization chamber should be protected during the water measurement by a tube with a wall thickness of 1 mm manufactured from polymethylmethacrylate. This tube should be attached to a holder that can be adjusted for measurements at various depths. The symmetry axis of the chamber must be positioned in the reference plane.

For electron energies in the range $1 \leq \bar{E}_0 \leq 10$ MeV the absorbed dose in the reference point should be measured in a solid phantom. A plane-parallel ionization chamber should be used (see supplement to be published).

The effective point of measurement for a cylindric ionization chamber is displaced from the centre of the chamber towards the radiation source (DUTREIX & DUTREIX 1966, HETTINGER et coll. 1967). However, for electron radiation, the centre of the cylindric chamber may be placed at the reference depth, as this is situated at a dose plateau or at least on a slow varying part of the depth ionization curve. For photon radiation, the chamber centre shall be placed at the reference depth, due to convenience. In this case correction factors are included in the total perturbation factors below in order to correct for displacement.

Measurements should be made for all combinations or irradiation conditions. A horizontal or vertical beam direction may be employed. With wedge fields, the edge of the wedge should be placed parallel to the symmetry axis of the ionization chamber. The measurements should be made at the two possible 180° different orientations of the wedge and the average result should represent the absorbed dose.

The Bragg-Gray equation is recommended for the determination of the absorbed dose at the reference point in the water in the absence of the chamber at the user's radiation quality, $D_{w,u}$. Thus,

$$D_{w,u} = \bar{D}_{air,u}\, p_u (s_{w,air})_u \qquad (10)$$

where

$\bar{D}_{air,u}$ = mean absorbed dose to air in the cavity of the ionization chamber measured in water at the user's radiation quality in Gy

$(s_{w,air})_u$ = mass stopping power ratio, water to air at the reference point at the user's radiation quality

p_u = total perturbation factor including corrections for lack of water equivalence in the

Table 6

Recommended values of $(s_{w\,air})_u$ and p_u for photon radiation at the reference point in a water phantom. The variations of the stopping-power ratios with depth for depths beyond the absorbed dose maximum are considered to be negligible (NAHUM 1975)

Radiation beam quality	J_{100}/J_{200}	$(s_{w\,air})_u$*	$p_{u\,graphite}$**	$p_{u\,water}$**
^{60}Co-γ	1.97	1.150	0.970	0.990
4 MV	1.84	1.145	0.970	0.990
6	1.71	1.140	0.980	0.990
8	1.63	1.135	0.980	0.995
10	1.59	1.125	0.985	0.995
12	1.56	1.120	0.985	0.995
14	1.54	1.115	0.985	0.995
16	1.52	1.110	0.985	0.995
18	1.50	1.105	0.985	0.995
20	1.49	1.105	0.985	0.995
22	1.47	1.100	0.985	0.995
25	1.46	1.095	0.990	0.995
30	1.45	1.090	0.990	0.995
35	1.44	1.080	0.990	0.995
40	1.43	1.075	0.990	0.995
45	1.43	1.070	0.990	0.995
50	1.42	1.065	0.990	0.995

* Values from ICRU (1969).

** p_u-values from JOHANSSON et coll. (1977) for a cylindric ionization chamber with diameter 5 mm.

ionization chamber material at the user's radiation quality, perturbation of the fluence due to the insertion of the air cavity and location of the effective point of measurement of the cylindric chamber due to the curved ionization chamber wall; only for photon beams.

With the assumption that

$$N_D = \frac{\bar{D}_{air,c}}{M_c} = \frac{\bar{D}_{air,u}}{M_u}$$

the absorbed dose at the reference point in water is obtained from:

$$\boxed{D_{w,u} = N_D M_u p_u (s_{w\,air})_u} \qquad (11)$$

where

M_u = meter reading at user's quality corrected for temperature, pressure, recombination, humidity etc.; in C or div.

This is the essential equation for practical dosimetry work. p_u-factors for different radiation beam qualities and ionization chamber materials are given in Tables 5 and 6. $(s_{w,air})_u$ values are found in Table 7.

In the symbol $(s_{w\,air})_u$ is not specified the type of stopping power ratio. Two different sets of stopping power ratios should strictly have been used, one for a chamber of air equivalent walls and another for a chamber of water equivalent walls. In the first case Harder's extended Bragg-Gray cavity theory (HARDER 1965) is to be used, which means that it is assumed that a delta ray equilibrium exists in the air cavity due to the air equivalent wall, (i.e. the energy carried into the cavity by delta rays is balanced by energy carried out by delta rays). $(s_{w\,air})_u$ should then be the collisional mass stopping power ratio water to air. In the second case, Spencer-Attix theory is to be used. The distribution of the electron fluence down to a certain cut-off energy must then be known at the point of measurement in the water phantom and the restricted stopping powers should be used for this distribution. The cut-off energy is dependent on the size of the chamber. However, in electron beams the two sets of data differ with less than one per cent when using the mean electron energy calculated according to BRAHME (1975) for determination of the collision stopping power ratios in the Bragg-Gray-Harder theory and when using BERGER et coll. (1975) electron fluence distribution to determine the mass stopping power ratio in Spencer-Attix theory. Furthermore, experiments in both electron and photon beams with air equivalent and water equivalent chambers show that the same stopping power data within about one per cent could be used for the two types of walls (JOHANSSON et coll. 1977). Therefore, for simplicity, only one set of $(s_{w\,air})_u$ is recommended. The $(s_{w\,air})_u$ from BERGER et coll. (1975) are recommended for electron radiation and those from the ICRU (1969, Table A.3) for photon radiation.

Illustrative example

Calibration at standards laboratory. The national standards laboratory has performed a calibration of the ionization chamber, which has a diameter of 5 mm and a graphite wall of about 0.5 mm. A build-up cap of graphite was used at the calibration and the thickness of wall and cap together was 0.45 $g \cdot cm^{-2}$. The following information on the ionization chamber calibration factors are given in the calibration certificate:

The air kerma calibration factor, N_K obtained for the ionization chamber in the ^{60}Co-γ ray beam at the laboratory, at a field size 100 mm × 100 mm and a focus–detector distance of 1 m was found to be:

N_K = 1.10 Gy/div. at 22.0°, 101.33 kPa and 50% rel. air humidity

Table 7

Recommended values of $(s_{w,air})_u$ as a function of depth (z) and mean energy at the phantom surface $\bar{E}_0$ for electron radiation. The values are taken from BERGER *et coll. (1975) with energy cut-off Δ=15 keV, I(water)=71.3 eV and I(air)=92.9 eV*

Depth mm	$(s_{w,air})_u$							
	Mean energy at phantom surface E_0/MeV							
	1	2	3	4	5	6	7	8
1	1.136	1.112	1.092	1.074	1.058	1.043	1.031	1.019
2	1.144	1.124	1.101	1.081	1.065	1.049	1.037	1.025
4	1.151	1.137	1.112	1.090	1.072	1.056	1.042	1.031
6	1.157	1.147	1.122	1.099	1.080	1.063	1.048	1.037
8		1.154	1.132	1.108	1.088	1.070	1.055	1.042
10		1.157	1.142	1.118	1.097	1.078	1.061	1.048
12			1.150	1.129	1.106	1.086	1.068	1.055
14			1.155	1.139	1.115	1.094	1.074	1.061
16			1.157	1.146	1.125	1.104	1.082	1.068
18				1.151	1.134	1.112	1.091	1.074
20				1.155	1.141	1.121	1.100	1.082
25				1.156	1.153	1.141	1.120	1.102
30					1.154	1.151	1.137	1.123
35						1.152	1.148	1.139
40								1.147
45								1.146

Depth mm	$(s_{w,air})_u$							
	Mean energy at phantom surface $\bar{E}_0$/MeV							
	9	10	12	14	16	18	20	22
0	1.011	1.002	0.990	0.980	0.972	0.965	0.958	0.952
5	1.023	1.015	1.001	0.990	0.981	0.974	0.969	0.962
10	1.036	1.027	1.012	1.000	0.990	0.982	0.975	0.968
15	1.050	1.038	1.023	1.009	0.998	0.989	0.982	0.974
20	1.066	1.053	1.033	1.018	1.006	0.997	0.988	0.980
25	1.083	1.069	1.045	1.027	1.013	1.004	0.995	0.986
30	1.103	1.087	1.058	1.037	1.022	1.011	1.001	0.993
35	1.120	1.105	1.072	1.049	1.031	1.018	1.008	0.999
40	1.138	1.122	1.086	1.060	1.041	1.025	1.015	1.005
45	1.144	1.137	1.104	1.075	1.053	1.034	1.022	1.011
50		1.144	1.120	1.091	1.065	1.046	1.031	1.017
60			1.138	1.119	1.093	1.069	1.051	1.035
70				1.135	1.117	1.093	1.072	1.055
80					1.127	1.114	1.094	1.073
90						1.129	1.118	1.097
100							1.128	1.118
110							1.121	1.124
120							1.105	1.115

Depth mm	$(s_{w,air})_u$					
	Mean energy at phantom surface $\bar{E}_0$/MeV					
	25	30	35	40	45	50
0	0.944	0.931	0.923	0.917	0.912	0.907
10	0.959	0.945	0.935	0.926	0.921	0.917
20	0.971	0.956	0.944	0.934	0.928	0.924
30	0.981	0.965	0.952	0.942	0.934	0.930
40	0.992	0.974	0.960	0.949	0.940	0.935
50	1.003	0.983	0.968	0.956	0.946	0.940
60	1.016	0.993	0.977	0.963	0.953	0.946
70	1.030	1.004	0.986	0.971	0.960	0.952
80	1.047	1.016	0.995	0.979	0.967	0.958
90	1.065	1.030	1.006	0.988	0.974	0.964
100	1.085	1.045	1.017	0.997	0.982	0.971
110	1.112	1.062	1.030	1.006	0.991	0.979
120	1.122	1.079	1.043	1.017	0.999	0.986
130	1.117	1.101	1.058	1.028	1.008	0.994
140	1.105	1.113	1.073	1.041	1.018	1.002
160	1.099	1.105	1.103	1.068	1.040	1.019
180		1.094	1.101	1.094	1.064	1.038
200			1.088	1.094	1.088	1.062
220				1.081	1.088	1.082
240				1.083	1.075	1.085
260					1.072	1.072
280						1.065

The absorbed dose to air (inside the cavity) ionization chamber factor N_D, recommended in the present protocol, is

$$N_D = N_A\, k_{att}\, k_m (1-g)$$

N_A = 1.10 Gy/div
k_{att} = 0.990
k_m = 0.991
g = 0.004

$\Rightarrow$ N_D = 1.075 Gy/div. at 22.0°, 101.33 kPa and 50% rel. air humidity

Measurements in an electron beam. (1) A depth ionization curve is measured for a large beam size at SSD≈1.0 m in order to determine the mean energy of the electrons at the phantom surface, $\bar{E}_0$. In the measurements the effective point of measurement (p. 17) is used. The depth at which the ionizations are reduced to 50 per cent (R_{50}) is determined to 84 mm. From Fig. 3 the corresponding $\bar{E}_0$-value is obtained and $\bar{E}_0$=20 MeV.

(2) From the depth ionization curve a depth absorbed dose curve is calculated using $(s_{w,air})_u$-factors from Table 7. The depth of the maximum absorbed dose was found to be 30 mm. The absorbed dose at

this reference depth is then determined from a measurement with the centre of the ionization chamber at this depth. Insertion of the meter reading, M_u, (corrected for temperature, pressure, recombination etc.) and p_u- and $(s_{w,air})_u$ factors from Table 5 in eq. (X) gives the absorbed dose in water at the reference point:

$$\left.\begin{aligned} D_{w,u} &= N_D M_u p_u (s_{w,air})_u \\ N_D &= 1.075 \text{ Gy/div.} \\ p_u &= 0.990 \\ (s_{w,air})_u &= 1.001 \end{aligned}\right\} \quad D_{w,u} = 1.065 M_u \text{ Gy}$$

Measurements in a photon beam (1). The photon beam quality was estimated from the ratio J_{100}/J_{200}, which was 1.51. This corresponds roughly to a maximum photon energy of 17 MV according to Table 6 or Fig. 4. The reference depth is then obtained from Table 3 as 100 mm. The absorbed dose at this depth is measured with the centre of the ionization chamber at this point. If M_u is the meter reading (corrected for temperature, pressure, recombination etc.) eq. (11) and Table 6 give

$$\left.\begin{aligned} D_{w,u} &= N_D M_u p_u (s_{w,air})_u \\ N_D &= 1.075 \text{ Gy} \\ p_u &= 0.985 \\ (s_{w,air})_u &= 1.108 \end{aligned}\right\} \quad D_{w,u} = 1.173 M_u \text{ Gy}$$

(2) The absorbed dose at dose maximum is determined from the ratio of the depth ionization at 100 mm and dose maximum. The depth ionization curve is used for evaluation of this ratio. (The effective point of measurement, 0.75 r, should be used in measuring depth ionization curves.)

Determination of absorbed dose at any point

Relative absorbed dose distributions should be related to the absorbed dose at the reference point, which should therefore be included in all distribution determinations. The distribution should apply to a large water phantom (page 14). A complete set of distributions should be available for all combinations of energy, field sizes, SSD, etc. that are in use for radiation therapy. The hospital physicist is responsible for all modifications of these distributions in clinical practice, for instance the insertion of lead block and bolus.

Beam axis absorbed dose distribution

Electron beams. The beam axis depth absorbed dose distribution cannot be specified in a unique way from electron beam parameters such as energy, field size and SSD. The shape of the distributions is dependent on a large number of constructional details of the accelerators and they are only partly contained in the beam parameters. Therefore, as a rule, the distributions should be determined for each accelerator. When accelerators of the same design are used (SVENSSON 1971), common beam axis depth dose distributions may be applied by departments only after a check of some distributions by measurements. Significant differences may appear as a result of individual adjustments and small differences in thickness of accelerator window, foils, and in collimator design etc.

The relative depth absorbed dose distributions could be measured with ionization chambers, semiconductor detectors, liquid-ionization chambers or ferrous-sulphate dosemeters. The choice of method depends on the instruments that are locally available. The relative distributions should be checked against depth absorbed dose curves measured with an ionization chamber method or possibly, when available, ferrous-sulphate dosemeters.

The ionization chamber method is well established for measurements at depths equal to or larger than that of the dose maximum. In the measurements of relative depth ionization curves the displacement effect of the ionization chamber should be taken into account for cylindric chambers. This effect should be corrected for by using an effective point of measurement. This point has been determined by extrapolating the geometric displacement of the depth ionization curves, measured by different sizes of cylindric chambers to a zero size chamber. In the experimental determination the perturbation effect was not considered, so this is automatically corrected for in the use of the effective point of measurement. The effective point of measurement varies slightly with the electron energy $E_{p,0}$ and phantom depth and is 0.5 r to 0.75 r in front of the chamber centre, where r is the radius (HETTINGER et coll. 1967, DUTREIX & DUTREIX 1966, JOHANSSON et coll. 1977). A value of 0.5 r is recommended for electron radiation. The recombination losses can be disregarded in the measurement of relative depth ionization curves for those chambers recommended in the present protocol for most treatment units. The relative depth ionization curves should be multiplied with $(s_{w,air})_u$ (Table 7) for different depth in order to convert these curves to relative depth absorbed dose curves.

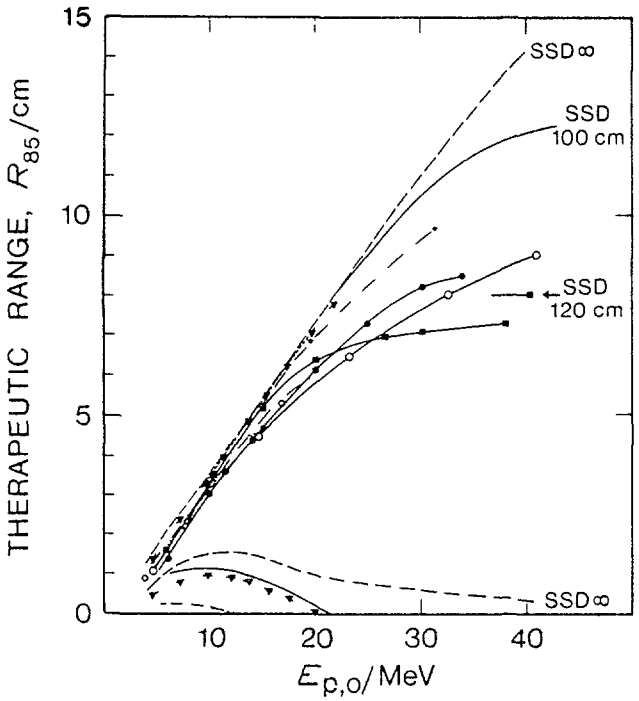

Fig 6 The therapeutic range R_{85} for large field sizes as a function of the most probable energy at the phantom surface E_{p0} The SSD=1 m if not otherwise stated Experimental points are indicated with different symbols for different accelerators The upper two curves are theoretic data from BERGER & SELTZER (1969), the SSD=1 m curve is derived from inverse square law corrections Near surface, lines are obtained for those beams with $D_s/D_m<0$ 85

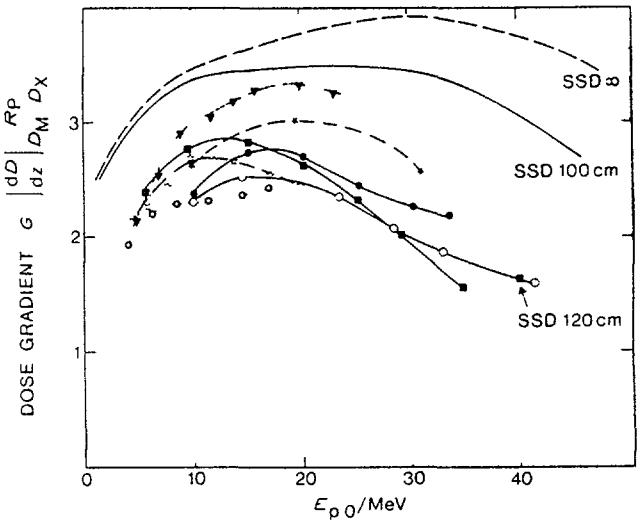

Fig 7 Dose gradients, G, for large field sizes as a function of the most probable energy at the phantom surface, E_{p0} The SSD= 1 m if not otherwise stated Experimental points are indicated with different symbols for different accelerators The upper two curves are theoretic data from BERGER & SELTZER (1969) the SSD=1 m curve is derived from inverse square law corrections

At small phantom depths the air ionization method might introduce uncertainties due to contamination of low energy electrons and an incomplete build-up of δ-ray spectrum If measurements at such depths are desired a liquid ionization chamber (HULTEN & SVENSSON 1975), or thin ferrous sulphate dosemeters (SVENSSON & HETTINGER 1967) could be recommended Since, in general, it is only necessary to make these measurements in the calibration procedure after an accelerator installation, joint measurements by different departments are recommended

It is often useful to investigate the therapeutic and physical properties of an electron beam and describe them by some simple parameter There are several reasons for introducing such parameters (BRAHME & SVENSSON 1976), thus: 'the increasing number of electron accelerators of different types and often quite different beam qualities necessitates a simple unified comparison of the quality of one beam with another; the desirability of simple and accurate beam diagnostics make it useful to focus attention on a few independent parameters characterizing the beam quality, and finally, from a therapeutic point of view, it is important to define the treatment volume in a relevant and consistant way, not least to simplify comparisons between different treatment centres'

The parameters that are recommended for use appear in Fig 2 D_m the maximum absorbed dose along the beam axis, D_s the surface absorbed dose at 0 5 mm depth (this depth has been chosen as it is accessible for accurate absorbed dose measurement and as it approximately corresponds to the radiation sensitive layer below the epidermis), D_x the photon background, G the absorbed dose gradient, R_{100} the depth of the absorbed dose maximum, R_{85} the therapeutic range, R_{50} the half value depth and R_p the practical range

Of particular importance for an electron beam are R_{85} and G Experimental and theoretic values for broad beams are given in Figs 6 and 7 A dose-gradient below about 2 5 for large beams indicates that the scattering system and collimating system are of poor design and that unnecessary large volumes of normal tissue are irradiated in single beam technique

Photon beams The beam axis depth absorbed dose curves are less critically dependent on the beam parameters and simpler to measure than for electron radiation. All the dosemeter systems mentioned for electrons can be used but should be checked against the air ionization method The difference between the relative depth absorbed dose

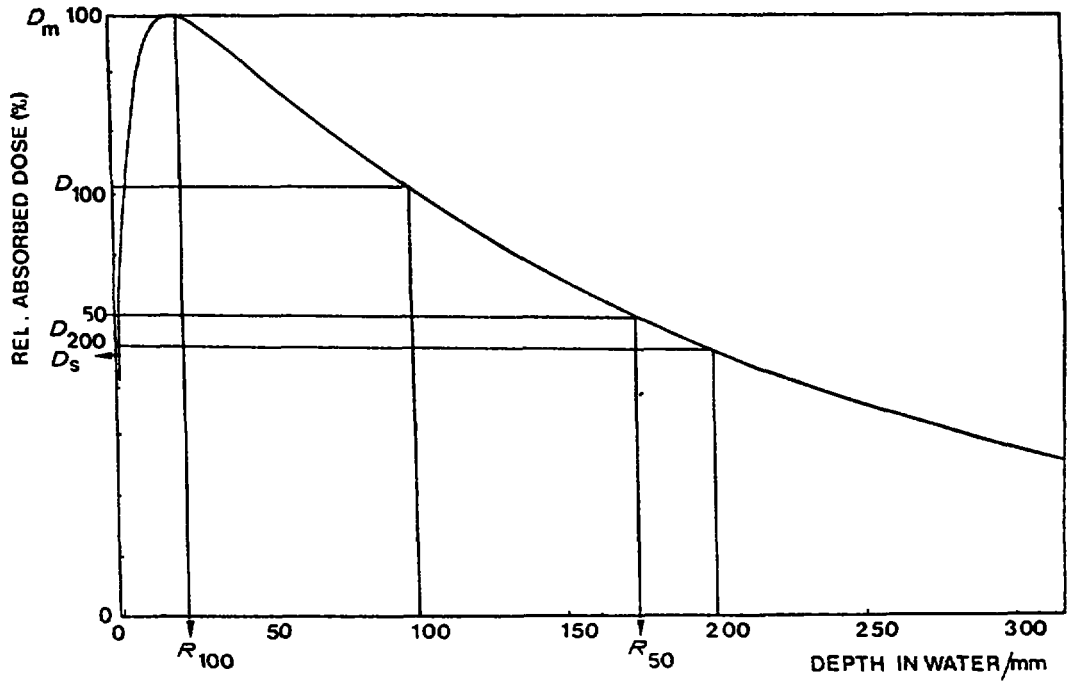

Fig. 8. Beam axis depth absorbed dose distribution for photon beams. Parameters often used to characterize the quality of the distribution are indicated. $D_{100}/D_{200} \approx J_{100}/J_{200}$ which is input parameter for $(s_{w\,air})_c$ in Table 6.

and depth ionization curves, when both are normalized at maximum, may be 1 to 2 per cent at a large depth (SVENSSON 1971, NAHUM 1975). These differences can be disregarded for practical dosimetry. In the measurement of depth ionization the displacement effect must be considered and the effective point of measurement must be used. The effective point of measurement varies slightly with energy and phantom depth (HETTINGER et coll. 1967, JOHANSSON et coll. 1977). A value of 0.75 r is recommended for all energies and phantom depths. The variations can be disregarded in practical dosimetry. Published depth dose data for different peak energies are available for different accelerators. Those data should be checked by measurements of a few distributions both at small and large field sizes.

Parameters describing the physical and therapeutic properties of the beam axis absorbed dose distributions are also useful for photon radiation. D_s, D_m, R_{100}, R_{50} are defined as for electron radiation (Fig. 8). The ratio J_{100}/J_{200} is discussed on page 8 and is of importance for the choice of stopping power ratios.

Iso-absorbed dose distributions

A semi-conductor detector connected to an automatic recorder may be used for the absorbed dose distribution determination in a water phantom for both photon and electron radiation beams. This method is simple as the isodoses are directly plotted and corrections are often not necessary to carry out. The spatial resolution is good as the sensitive layer of the detector is less than a few mm^2. Systematic errors could, however, be introduced for some accelerators, especially for betatrons, dependent on the radiation pulse shape and neutron contamination. Furthermore, the curves measured with the semi-conductor may differ from the relative isodose curves at small phantom depths (BRAHME & SVENSSON 1976). The method should, therefore, be checked against ionization chamber measurements or possibly, when available, ferrous-sulphate dosemeters.

The absorbed dose of electron beams at points outside the beam axis may be assessed by means of photographic film placed parallel to the beam axis in polystyrene phantoms. A significant difference between the relative depth absorbed dose curve and the relative depth blackening curve exists at depths smaller than 20 mm (LOEVINGER et coll. 1961, HETTINGER & SVENSSON 1967). The beam axis depth absorbed dose curve is first measured and is then used to assign a depth absorbed dose value to all points along the beam axis in the film. Isodensity curves joining points in the film with the same net blackening are assigned to the depth absorbed dose

Table 8

Suggestion of a maintenance program for accelerators and ^{60}Co-γ units

Check of		Frequency of check				
		Once a day	Once a week	Once a month	Once a quarter	Once a year
Light beam and pointers	p. 20	^{60}Co acc.				
Radiation beam and light beam agreement	p. 20 fig. 5		^{60}Co acc.			
All mechanical alignments	p. 20 HPA (1970) AAPM (1975)					^{60}Co acc.
Abs. dose monitor and patient dose agreement	p. 21	^{60}Co acc.				
Abs. dose monitor calibr. factor constancy	p. 21		acc.	^{60}Co		
Abs. dose monitor calibr. factor (in)dependence of diff. param.	p. 21			acc.	acc.	
Energy constancy	p. 21		acc.			
Radiation beam uniformity	p. 21		acc.			^{60}Co

at the point where they pass the beam axis. It is frequently sufficient to construct the isodensity curves without correcting for background blackening.

The same method for photon beams as for electron beams may be employed although the accuracy of this method in the penumbra region is less satisfactory. The film method is often less accurate than measurements with semi-conductor detectors. Another approach is to use transversal measurements at 4 depths with an ionization chamber (decrement line method; ORCHARD 1964, ORR et coll. 1964) followed by computer calculation of the isodose curves (KALNÆS & MUNK 1972).

Maintenance program for the dosimetry of therapy units

The dosimetry data, on which the irradiations are based, shall be checked regularly for constancy. The number of checks may depend to some extent on the behaviour of the particular therapy unit and its intended use. If previous examinations indicate few and slow changes some decrease in their frequency may be satisfactory. A maintenance program for ^{60}Co-γ units and accelerators is suggested in Table 8, where the frequencies are given on the assumption, that dual absorbed dose monitoring (page 21), exists and that measurements of absorbed doses on patients are performed (page 22). All technical checking procedures prescribed by the manufacturer should be followed.

The responsible physicist should for each therapy unit write instructions on how to carry out the relevant checks and their frequencies. A logbook for recording these measurements shall be kept.

Radiation beam alignment checks

A simple check on the light beam should be carried out daily. A white card on which is drawn a square field is placed at the normal SSD. With use of the numerical field size indicator a corresponding field size is set up and the light field is compared with the drawing. Without moving the card this comparison is again performed after the radiation head is rotated through 180°. It shall be checked that the cross-hair light image and the front pointer indicate the centre of the light field and that the cross-hair is projected on the back pointer tip.

Checks of agreement between the light beam and the radiation beam should be performed every week and each time the light beam bulb is exchanged. It is often convenient to combine this check with that of the radiation beam uniformity. The agreement should fulfil the values given in Geometric considerations (page 10).

Once a year a thorough alignment test should be performed. Detailed information on relevant procedures has been given (HPA 1970, AAPM 1975).

Absorbed dose monitor checks

Whenever performed the measurements of absorbed doses on patients should be checked for agreement with the absorbed dose monitor.

On accelerators the constancy of the absorbed dose monitor calibration should be checked weekly. It shall be possible to relate this check to the primary absorbed dose calibration of the monitor. A special phantom made of plastic should be used because of the convenience of handling. The position of the dosemeter should be close to the reference depth (Table 3). As several different reference depths might be of interest, the phantom may consist of a basic block together with a series of slabs marked and used for this purpose only. Monthly to quarterly a suitable series of such measurements should be performed for testing the monitor precision and stability and for examination of the calibration factors for independence on monitor setting, absorbed dose rate, beam direction, temperature, and air pressure. Also the dependence of the calibration factor on wedges and field size, flattening filter or scattering foils should be checked for constancy.

On ^{60}Co-γ units the check of the absorbed dose monitor calibration may be less frequent but at least once a month. The check reveals timer errors, changes in 'shutter effects' and possible changes in absorbed dose rate caused by, for instance, redistribution of the source (HANSEN 1972).

The ratio between the monitor reading and the determined absorbed dose value shall not deviate by more than ± 2 per cent from the ratio determined at the original measurements.

Radiation energy constancy checks

On therapy units which could have an unintentional change in the selected radiation energy (i.e. betatrons, linear accelerators) the energy constancy should be checked once a week. This is performed by checking the constancy of a ratio, J_1/J_2, between ionization measurements at two different depths. The phantom for check measurements of absorbed dose monitor calibration should be used and J_1 is the measurement at the reference depth. J_2 is measured with an additional slab plastic material in front of the phantom. For photon beams this slab should be approximately 10 cm thick and for electron beams about R_{50} minus the reference depth (Fig. 2, Table 3). The best geometric reproducibility is obtained if the source chamber distance is unaltered between measurements. In some irradiation geometries this is not possible and the SSD should instead be kept constant. The ratios, J_1/J_2, should be related to the relevant energy calibrations, and the plastic slabs should be marked and used for this purpose only.

The ratios J_1/J_2 should not deviate by more than ± 1 per cent from the original ratios for photon beams. For electron beams the deviation should be less than ± 4 per cent.

Radiation beam uniformity checks

The uniformity should be checked with the photographic film method (page 10). In each check the maximum blackening of the film and the blackening along the major axes and diagonals of the field should at least be determined. A full evaluation of the film blackening is of great value as the uniformity index then may be determined. The check should be made weekly with cyclic permutation of some relevant irradiation conditions (e.g. radiation quality, beam direction and field size), i.e. each combination is checked at least every month. The minimum requirements given in the section Geometric considerations should be fulfilled in all uniformity measurements.

Checks of absorbed dose given to the patient

The absorbed dose given to each patient shall be under proper control (ICRP 1970, LINDELL 1976, ICRU 1976). For this purpose dual absorbed dose monitoring systems and measurements of the absorbed dose on patients are recommended. The dual monitoring system shall protect the patient against overdoses caused by equipment failures. The patient dose measurements should detect any erroneous absorbed dose caused by equipment malfunctions and human mistakes so that proper corrections in the following treatments can be performed.

Absorbed dose monitoring systems

Malfunctioning of ^{60}Co-γ unit timers have been reported (VELKLEY 1975). Also mechanical malfunctions in the beam control system (sticking shutter, broken return spring, etc.) have caused excessive and unknown absorbed doses to patients. It is recommended to provide ^{60}Co-γ units with two independent timer systems both capable to give a termination signal to the beam control system. Detailed recommendations are given in Radiotherapy Ap-

paratus Safety Medical Panel (RASMP 1975). Dual timer systems coping with these recommendations are commercially available.

Accelerators shall be provided with two independent absorbed dose monitoring systems which to advantage should have physically separated radiation detectors. At least one detector system shall consist of a transmission chamber and measure the full beam at the patient side of any flattening filter or scattering foils. Both monitors shall be capable of independently terminating the irradiation. The integrated signals from the detectors should be digitally displayed on the console and at least one monitor should start from zero at the beginning of an irradiation. The readings of at least one display instrument should be preserved in the event of any failure (including power failure) or interruption of the irradiation. It should not be possible to start another treatment before the dose monitors and the presettings are reset. The absorbed dose rate shall be indicated on the console and for each increment of the dose monitor readings an acoustic beat should be given. If the dose rate exceeds a certain preset level (e.g. twice the normal dose rate), automatic termination of the irradiation should result. From the radiation detectors signals should be derived, which are proportional to the output in different parts of the radiation beam, so that the beam uniformity can be detected. An abnormal uniformity should result in an automatic termination of the irradiation. For a given radiation quality the dependence of the dose monitor calibration factor on dose rate, beam direction, temperature, and air pressure should be within 2 per cent. The dependence on beam energy, field size, and flattening filter or scattering foil should be less than ±30 per cent.

Absorbed dose measurements on patients

Absorbed dose measurements on patients could be divided into two levels of security. For 'level one , measurements are made at one of the first treatment occasions and every time a parameter (including patient anatomy) is changed. This enables detection of systematic mistakes in the decided irradiation procedure. 'Level two' measurements are made at every treatment occasion enabling detection of occasional operator mistakes and equipment failures.

Preferably level one measurements should be carried out in more than one point of the field. A further improvement may be obtained in the reduction of the number of occasional operator mistakes if level one measurements are correlated to a 'select and confirm' system. Occasional changes in patient positioning and occasional equipment failures could, however, be revealed only by level two dosimetry. On older radiation units with only one dose monitor system level two measurements may also replace a secondary dose monitor. A thorough discussion of possible errors and control of the absorbed dose to the patient for specific therapy procedures is given by MÖLLER et coll. (1976).

Patient dosimetry systems to be used routinely should besides reasonable precision possess simplicity of handling. The demand for precision is determined by an action level for open beams of ±3 per cent. For beams modified by a wedge or compensating or blocking filter an action level of ±5 per cent should be used. At least small condenser ionization chambers (Sievert chambers), thermoluminescent dosemeters (TLD) and small semiconductor detectors with suitable (partial) build-up caps can fulfil these requirements.

Appendix

For a proper understanding of the protocol some definitions are necessary, taken from ICRU (1976), HPA (1970) and NACP (1972), or slightly modified.

Beam: The electron or photon beam is the region in space traversed by photons or electrons from the source. Its edges are determined by the collimator, its cross sections perpendicular to the beam axis is the field and its direction is that of photon or electron travel.

Beam axis: Four types of beam axes can be defined. In a properly adjusted system all four axes will coincide. The definitions are:

(1) Mechanical definition: The *collimator rotation axis* is defined as the rotational axis at the collimator head.

(2) Geometric definition: The *geometric beam axis* is defined as the line passing through the centre of the beam flattening filter (or the main scattering foil or focus of scanning magnet system) and the centre of the final beam limiting diaphragms.

(3) Radiation definition: The *radiation beam axis* (sometimes named reference axis) is defined as the line passing through the centre of the effective radiation source and the centre of gravity of the area within which the absorbed dose exceeds 50 per cent of the maximum absorbed dose at the reference plane in a phantom.

(4) Light beam definition: the *light beam axis* is defined as the line from the effective light source and the centre of gravity of the area within which the light intensity exceeds 50 per cent of the maximum light intensity at the phantom surface.

Reference plane: The reference plane is defined as the orthogonal plane to the reference axis at a given depth beneath, and parallel to, the phantom surface. Recommended values for the depth are given in Table 3.

Reference point: The reference point is defined as the point of the inter-section between the reference plane and the beam axis (reference axis).

Radiation field size: The field size is defined in a phantom at the depth of the reference plane, with *that* plane at the proposed treatment distance. The field size is the area inside the 50 per cent level of the absorbed dose in the reference point. The numerical values of the field size are given as the distance between the 50 per cent level at the edges of the major axes, or the diameter of the 50 per cent level in a circular field.

Light field size: The light field size is defined at the surface of a phantom, with the surface at the proposed treatment distance. The light field size is the area inside the 50 per cent boundary of the light intensity; the light intensity in the centre being 100 per cent. The numerical values of the field size are given as the distance between the boundary of the major axes.

Uniformity index: The uniformity index is defined in the reference plane for a specified quantity (e.g. absorbed dose, ionization, net film density or current from a semi-conductor detector) as the ratio of the area containing points where this quantity exceeds 90 per cent of its value at the reference point and the area where it exceeds 50 per cent of the reference point value.

Physical penumbra: Physical penumbra is for a specified quantity as the lateral distance at the major axes between the 80 per cent and the 20 per cent of points of this quantity with the value at the reference point defined as 100 per cent.

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