SSDL Newsletter

IAEA/WHO NETWORK OF SECONDARY STANDARD DOSIMETRY LABORATORIES

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EDITORIAL NOTE

In an attempt to follow and implement developments in ionization chamber dosimetry the IAEA Dosimetry Laboratory has during the last years provided SSDLs in the Network with calibration factors both in terms of air kerma (N_K) and in terms of absorbed dose to water ($N_{D,w}$). Recent activities by at least two SSDLs have resulted in substantial dosimetric errors (close to 10%) due to the misinterpretation of the $N_{D,w}$ factor, which has been used instead of the chamber factor N_D of the IAEA Code of Practice, TRS-277; in one case a considerable number of radiotherapy patients were treated before the error was corrected. Staff from other SSDLs have expressed their confusion with the two calibration factors that require different formalisms and yield slightly different absorbed dose to water in ^{60}Co beams, as well as their doubts on the policy to be followed with hospital users.

This issue of the SSDL Newsletter is opened with recommendations on the use and dissemination by the SSDLs of $N_{D,w}$ factors; these should not be transferred to hospital ionization chambers or used by SSDLs for calibration of therapy beams until a new Code of Practice, replacing TRS-277, becomes available. The present IAEA *protocol* should be recommended and strictly followed in hospitals, and for this purpose only the air kerma calibration factor N_K is needed. The recommendations are followed by a note clarifying the difference between N_D (better called $N_{D,air}$) and $N_{D,w}$, together with details on the correction for the effect of metallic central electrodes.

A new international Code of Practice for dosimetry is being published. It will appear within the IAEA "Technical Report Series" as the number TRS-381. The new report entitled "THE USE OF PLANE-PARALLEL IONIZATION CHAMBERS IN HIGH ENERGY ELECTRON AND PHOTON BEAMS: AN INTERNATIONAL CODE OF PRACTICE FOR DOSIMETRY" complements TRS-277 in a field where much activity has occurred during the last years and updates various aspects of TRS-277 also related to cylindrical ionization chambers. An introduction of the new Code of Practice is given in this issue, reproducing a presentation in the IAEA Regional Seminar on "Radiotherapy Dosimetry: Radiation Dose from Prescription to Delivery", held in Rio de Janeiro (Brazil) in August 1994 (the proceedings of this seminar are now in press as an IAEA Tec-Doc).

A description of the on-going and planned activities of the IAEA Dosimetry Section is also presented in this issue, which also contains updated information on some cylindrical ionization chambers commercially available; modifications to this table will be included in future issues of the SSDL Newsletter whenever the Network secretariat finds it convenient.

As a regular contribution from this issue of the SSDL Newsletter and onwards, a list of members of the IAEA/WHO Network of SSDLs will be provided. Please review it carefully and inform the Network secretariat promptly if some information is not correct.

IAEA Dosimetry Section staff changes

Dr. Kalman Zsdanszky, well known to most people having contact with the Dosimetry Section over the last ten years, retired from the Agency at the end of 1995; he has returned to Budapest, Hungary, where now enjoys a well deserved rest together with his family. Dr. Peter Nette, former Unit Head of the Dosimetry Laboratory in Seibersdorf, leaves the Agency in March 1996 and returns to Rio de Janeiro, Brazil. Until a new candidate is appointed Dr. Kishor Mehta acts as Head of the Dosimetry Laboratory and Dr. Joanna Izewska (Warshaw, Poland) will hold a temporary position as TLD Officer.

Call for contributions to the SSDL Newsletter.

To increase the exchange of information between readers of the SSDL Newsletter and the Network secretariat, as well as between the members of the Network, readers are encouraged to submit manuscripts describing their work. The largest interest is on new or upgraded activities implemented in laboratories, contributions to Quality Assurance programmes in radiotherapy facilities, etc.

RECOMMENDATIONS ON THE USE AND DISSEMINATION OF CALIBRATION FACTORS IN TERMS OF ABSORBED DOSE TO WATER, $N_{D,w}$

The Dosimetry Section has recently detected some beam/monitor calibration errors at hospitals, originated by the calibration of ionization chambers at SSDLs, as well as mistakes in the annual reports submitted by SSDLs. It has been found that the errors were caused by the wrong use of the calibration factor $N_{D,w}$. The factor is currently provided by the IAEA Dosimetry Laboratory in calibration certificates to SSDLs.

As is well known, when an ionization chamber has a calibration factor in terms of absorbed dose to water, $N_{D,w}$ at the reference quality of ^{60}Co, the absorbed dose to water D_w at the reference depth of 50 mm in a water phantom irradiated with ^{60}Co gamma-rays is determined by measurements of the charge collected with the chamber center (reference point) placed at the reference depth. D_w is given by

$$D_w[mGy] = Q[nC] \times N_{D,w}^{Co-60}[mGy/nC]$$

where Q is the absolute value of the charge collected by the ionization chamber corrected for influence quantities (P, T, humidity, recombination, etc).

Note that the dosimetry procedure actually recommended by the IAEA (Absorbed Dose Determination in Photon and Electron Beams: An International Code of Practice, IAEA Technical Report Series no. 277, 1987) yields the absorbed dose to water at the position of the effective point of measurement of the chamber. For ^{60}Co gamma rays this is a point shifted from the center towards the radiation source a distance equal to 0.6 r*), where r is the internal radius of the chamber cavity. This difference in the depth where D_w is determined (for a chamber in a fixed position) should be taken into account using the corresponding difference in %DD at the two depths when comparisons of D_w using N_K or $N_{D,w}$ are made.

It should be noted that until the Agency develops its own Code of Practice for absorbed dose determinations in therapeutic photon and electron beams, based on calibrations of ionization chambers in terms of absorbed dose to water (as opposed to TRS-277 in terms of K_{air}), and to insure consistency in the IAEA/WHO network of SSDLs, the following recommendations to Secondary Standard Laboratories are given:

i) $N_{D,w}$ calibration factors provided by the Agency to SSDLs are only to be considered for the development at the SSDLs of the new calibration technique, which in the future will probably replace the present K_{air} -based method.

ii) The Agency will not provide $N_{D,w}$ calibration factors for clinical use until a new Code of Practice, replacing TRS-277, becomes available.

iii) SSDLs are advised not to distribute $N_{D,w}$ calibration factor to users for clinical purposes until the new Code of Practice becomes available. It is of especial importance to be aware of the possibilities of confusion for the hospital users, and therefore risks for radiotherapy

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*) Note that the value of 0.5 r provided in TRS 277 was superseded by the present value in SSDL Newsletter No. 31, December 1992. Other updates, mainly in connection with X-ray dosimetry, were also given there.

treatments, if $N_{D,w}$ calibration factors are distributed without appropriate recommended procedures for its use. The risk for errors is even larger if high-energy X-ray beams from accelerators are used.

iv) Reference values for D_w provided by the Agency and the SSDLs in TLD Postal Services and Quality Audits of D_w shall be based on the IAEA Code of Practice, TRS-277. This is so in order to avoid inconsistencies, where the Agency recommends Member States to base determinations of D_w on TRS-277 but some Laboratories use $N_{D,w}$. It is important to be aware that this is a method still under development in major laboratories and that at present a satisfactory agreement has not been reached yet. In the case of using $N_{D,w}$ supplied by BIPM, for example, this yields an unexplained difference with TRS-277 in D_w varying between 0.5 - 1.0 % for many ionization chambers, which is approximately of the same order as the difference among some Primary Standard Laboratories.

The Agency will, on the other hand, use $N_{D,w}$ calibration factors for developing purposes, and in research projects both N_K and $N_{D,w}$ calibration factors will preferably be used.

The secretariat of the IAEA/WHO Network of SSDLs strongly recommends that SSDLs do NOT supply the $N_{D,w}$ calibration factor to hospitals until an international Code of Practice incorporating this calibration factor becomes available.

A NOTE ON THE CALIBRATION FACTORS $N_{D,w}$ AND N_D. CORRECTIONS FOR THE CENTRAL ELECTRODE.

Because calibration factors can be obtained for different quantities and in different beam qualities, whenever a possibility for confusion exists a subscript will be added to the calibration factor. In this way the first index will denote the calibration quantity, the second the medium where the quantity is measured, and the third the quality of the beam used for calibration. For simplicity, $N_{D,w}$ without additional subscript refers always to the reference quality ^{60}Co. If necessary an index "Co" refers to ^{60}Co γ-rays, "X" to high-energy photons, and "E" to electron beams, $N_{D,w,Co}$, $N_{D,w,X}$, and $N_{D,w,E}$ respectively.

$N_{D,air}$ Is the absorbed-dose-to-air chamber factor. From the quantity determined with this factor, $\overline{D}_{air}$, the absorbed dose to water in a point, D_w, is derived by the application of the Bragg-Gray principle. **This factor was called N_D in TRS-277**, but the subindex air has been included here to specify without ambiguity that it refers to the absorbed dose to the air of the chamber cavity. This is the N_{gas} of AAPM TG-21. In a forthcoming IAEA Code of Practice it is given by

$$N_{D,air} = N_K (1-g)\, k_{att} k_m k_{cel}$$

which is similar to the formulation given in some other protocols where the factor k_{cel} also appears explicitly. TRS-277 did not include k_{cel} in the equation for N_D and therefore this latter factor did not relate solely to the geometrical characteristics of the chamber, i.e. an indirect measure of the cavity volume; k_{cel} was instead included in the $p_{cel-gbl}$ factor (see below). The numerical value of $N_{D,air}$ for cylindrical chambers with 1 mm diameter aluminium electrodes (NE-2571) is a factor 1.006 greater than N_D as given in TRS-277. Although the determination of the $N_{D,air}$ chamber factor by the user should strictly not be considered as a calibration, the use of a reference chamber with a calibration factor N_K supplied by a Standards Laboratory provides traceability to national and international standards.

$N_{D,w}$ Is the absorbed-dose-to-water chamber factor, which yields the absorbed dose to water (per electrometer reading unit) in the absence of the chamber at a point in water where the reference point of the chamber[1] is situated and at a reference beam quality Q_o. This symbol was given in TRS-277 but in practice its use was restricted to low-energy X-rays. The most common approach is to provide users with $N_{D,w}$ at a reference quality Q_o, usually ^{60}Co γ-rays, and apply beam quality correction factors for other beam qualities, high-energy

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[1] The point in the chamber specified by a calibration document to be that at which the calibration factor applies. **Not to be confused with the effective point of measurement of TRS-277.**

photon or electron beams. **Users should be warned of the possibility of confusion arising from the notation N_D used by AAPM TG-21 for the $N_{D,w}$ factor.**

k_{cel} Factor to take into account the non-air equivalence of the central electrode of a cylindrical (thimble) ionization chamber for obtaining $N_{D,air}$ from the calibration factor in terms of air kerma, N_K, at the reference quality Q_o, usually ^{60}Co γ-rays. As discussed in TRS-277, various investigations have demonstrated an increase in the response of a cylindrical ionization chamber to **^{60}Co irradiation in air** with increasing electrode diameter when the electrode is aluminium. This has been verified both experimentally and using Monte-Carlo simulations. In most cases the uncertainty in terms of one standard deviation was of the same order as the correction itself or even larger. Recent Monte-Carlo simulations of the effect of metallic central electrodes have decreased considerably the estimated uncertainty of the correction, yielding k_{cel} equal to 1.006±0.1% (uncertainty type-A) for a NE-2571 chamber with a 1 mm diameter aluminium central electrode; this is the value recommended in the new Code of Practice.

p_{cel} Factor that corrects for the effect of the central electrode of a cylindrical ionization chamber **during in-phantom measurements in ^{60}Co, high-energy photon and electron beams.** The product $k_{cel}\,p_{cel}$ was called p_{cel} in TRS-277, although it should have been named $p_{cel\text{-}gbl}$ to specify without ambiguity that it is a global correction factor[2]. In ^{60}Co beams the global correction for a Farmer-type chamber was equal to unity and this result has been confirmed. In electron beams it has been found that the global correction of 0.8% recommended by TRS-277 and other protocols did not produce a consistent determination of the absorbed dose in electron beams. Monte-Carlo simulations have supported the conclusion that the $p_{cel\text{-}gbl}$ factor recommended by TRS-277 is too large; identical corrections have been found for the existing solid and hollow electrodes. Using the latest results for ^{60}Co in air (k_{cel} equal to 1.006) and for high-energy electrons in a phantom (p_{cel} equal to 0.998), the global correction in electron beams amounts to 1.004 for a NE-2571 Farmer chamber, which is half of the correction recommended in TRS-277. This result is consistent with the analysis of the experimental results of various authors. The effect increases for low electron energies. The agreement between new sets of data confirms the need for a decrease in the correction factor recommended in TRS-277, and the data for p_{cel} in the new Code of Practice have been adjusted accordingly and separated from k_{cel}.

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[2] The reason to separate both components is not only to achieve a consistent definition of the $N_{D,air}$ chamber factor; during the calibration procedure in terms of $N_{D,w}$ only in-phantom measurements are involved and the use of the $p_{cel\text{-}gbl}$ factor is inappropriate. **The determination of the dose to water with cylindrical chambers using the $N_{D,air}$-based formalism is not modified by the separation of $p_{cel\text{-}gbl}$ (TRS-277) into its components k_{cel} and p_{cel}.**

ACTIVITIES OF THE IAEA DOSIMETRY SECTION

1. Introduction

The emphasis of the activities of the IAEA Dosimetry Section is today focused on services provided to developing Member States through the IAEA/WHO network of Secondary Standard Dosimetry Laboratories (SSDLs) and dose quality audits. The latter are performed through the IAEA/WHO TLD postal service to SSDLs and radiotherapy centres and the International Dose Assurance Service (IDAS) for radiation processing facilities, mainly for food-irradiation and sterilization of medical products. The organizational chart and activities of the Section are shown in Figure 1.

Significant attention is given to the physical and technical aspects of quality assurance (QA) procedures in radiotherapy and the development of educational programmes for medical radiation physicists, both conducted under Technical Cooperations (TC) and Coordinated Research Programmes (CRP). The transfer of dosimetry techniques, both for clinical and industrial applications are usually conducted in the form of CRPs. The development of technical reports, usually within the IAEA Technical Report Series, describing recommended procedures for the calibration of radiation equipment and therapeutic beams is one of the major goals of the Section.

The staff of the Dosimetry Section provides the programmatic responsibility, supervision and support required for the measurements at the Agency's Dosimetry Laboratory in Seibersdorf, where all the equipment is located. This consists of a Co-60 therapy unit and x-rays generators for the calibration of ionization chambers and radiation detectors for radiotherapy and radiation protection, a thermoluminiscence dosimetry (TLD) system, Electron Spin Resonance (ESR) equipment, and ancillary equipment. Besides, the Dosimetry Laboratory has an easy access to two Co-60 Gammacell-220 for calibration of dosimeters used for radiation processing.

The activities of the Dosimetry Section are reviewed bi-annually by an external Advisory Group (the SSDL Scientific Committee) that, acting as an independent auditor, verifies that the work performed by the Dosimetry Section covers the aims of the Agency's Subprogramme E.3. The Committee includes a member of the International Commission for Radiation Units and Measurements (ICRU) and of the International Bureau of Weights and Measurements (BIPM), and members of Primary and Secondary Standard Dosimetry Laboratories (PSDLs and SSDLs, respectively).

2. Secondary Standard Dosimetry Laboratory (SSDL) network

Until the eighties, most of the activities of the Dosimetry Section were concentrated in the development of a network of Secondary Standard Dosimetry Laboratories. The network was initiated as a joint project between the IAEA and the World Health Organization (WHO) and is known as the IAEA/WHO SSDL network. The secretariat of the network is located at the Agency's Dosimetry Section and its Head acts as the General Secretary of the network. The Agency's Dosimetry Laboratory is the central laboratory of the network, establishing the link to the International Metrology System. The SSDL network presently includes 73 laboratories and 6 SSDL national organizations in 58 Member States; the network also includes 14 affiliated members, mainly PSDLs, ICRU, BIPM, and other international organizations.

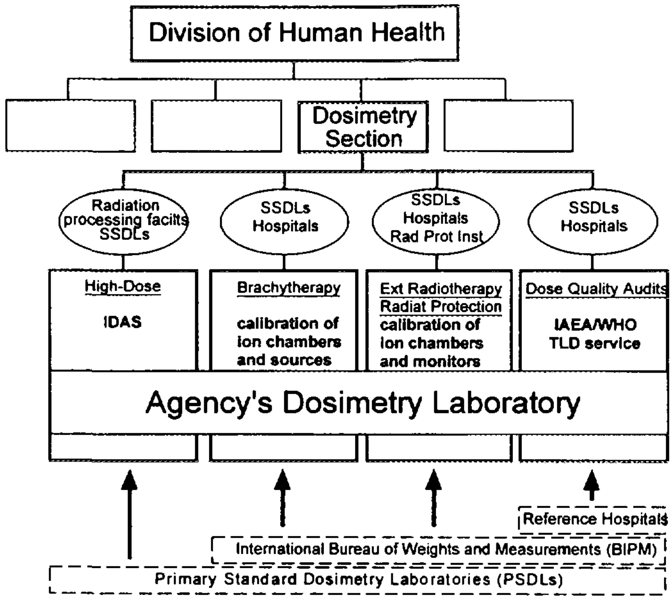

FIG. 1. Organizational chart of the Agency's Dosimetry Section, RIHU, showing the main fields of activity and services provided to Member States. Indicated are also the target users of the services and the organizations providing reference irradiations to the Dosimetry Laboratory.

In addition to contributing economically to the installations and purchase of equipment for SSDLs in the Member States, the programme to establish the network of SSDLs has the responsibility to guarantee that the services provided by the laboratories follow internationally accepted metrological standards. This is accomplished first with the transmission of the calibration factors for ionization chambers from PSDLs or the BIPM through the Agency's Dosimetry Laboratory. As a second step, follow-up programmes and dose quality audits are implemented for the SSDLs to guarantee that the standards transmitted to users in the Member States are kept within the levels required by the International Metrology System.

It must be emphasized, however, that one of the principal goals of the dosimetry chain is to guarantee that the dose delivered to the patients undergoing radiotherapy treatments in the Member States is kept within internationally accepted levels. During the last years the trend towards the implementation of QA procedures in radiotherapy has been based on the criticality of biological response to a precise and well defined radiation dose; the probabilities of tumour control and normal tissue complication are then closely related to a correct patient dosimetry. The activities of the IAEA towards the SSDL network have not only been addressed to establish "metrological institutions of high quality", but also to emphasize the support of the SSDLs to QA programmes for radiotherapy. This is accomplished not only by insuring that the calibrations of instruments provided by SSDLs are correct, but also by promoting the contribution of SSDLs to perform dosimetry quality audits in therapy centers, and if needed, performing calibrations of radiotherapy equipment at hospitals. Depending on the equipment and the staff available at the laboratory, and sometimes depending also on the functional organization of the SSDL, these activities vary between different countries.

During 1995 the Agency's Dosimetry Section has provided calibrations of 22 reference ionization chambers and dosimeters for 12 SSDLs. A total of 59 ionization chambers belonging to SSDLs and hospitals have been calibrated (410 calibration points at different radiation qualities). The quality audit system based on mailed thermoluminescence dosimeters (TLDs) has been applied to 60 SSDLs in order to verify their calibrations of Co-60 therapy units and medical accelerator radiation beams. The coherence and accuracy of the reference instrumentation of 15 SSDLs have been verified through intercomparison measurements using ionization chambers as transfer instruments.

A new programme to develop procedures for the calibration of radiation sources used in brachytherapy (intracavitary and interstitial) and related measuring equipment, first at the Agency's Dosimetry Laboratory and later at the SSDLs, has just been initiated; its full implementation is, however, conditioned by the limited staff available at the Dosimetry Laboratory.

3. Dose Intercomparison and Assurance

The second main project of the Dosimetry Section consists in dose quality audits for radiotherapy centres using mailed thermoluminescence dosimeters and the IDAS for industrial facilities where alanine-ESR dosimeters are sent to food irradiation and sterilization plants. In both services users are requested to irradiate the dosimeters with a given dose under known irradiation conditions; the dosimeters are then returned to the Agency's Dosimetry Laboratory and evaluated.

3.1. The IAEA/WHO TLD postal service

The TLD postal service is implemented through a collaboration between the Agency and the WHO. The Agency's Dosimetry Section is responsible for the technical aspects of the thermoluminescence system, reference irradiations, and collection and evaluation of the TLDs. WHO takes care of the distribution of the TLDs to radiotherapy institutions using WHO national or regional affiliated centres. Because the tasks of the Agency are usually performed in collaboration with government nuclear energy authorities in the Member States, the role of WHO is to establish the connection through the health ministries, where radiotherapy centers usually belong. This division of tasks is, however, a limitation to the efficient implementation of the programme in many instances, because it does not allow a direct communication between hospital users and the Agency. In exceptional cases dosimeters have been distributed directly by the Agency.

The IAEA/WHO TLD postal service performs dose checks for the therapy machines. TLDs are irradiated by the users in pre-determined reference conditions, using radiation doses of clinical relevance. The dose absorbed in the dosimeter is determined at the Agency's Dosimetry Laboratory and the result compared with the stated value. The service has been used by more than 2500 radiotherapy centers, and in many instances significant errors have been detected in the calibration of therapy beams with subsequent patient mistreatments that are close to the criterion of "radiological accident"; in all instances the service provides an independent and impartial quality audit of the dosimetry procedures. Originally the service was developed for Co-60 therapy units and it has recently been extended to high-energy photon and electron beams produced in clinical accelerators. Within this programme there are activities in collaboration with other organizations, such as the Pan-American Health Organization (PAHO), European Society for Therapy and Oncology (ESTRO), Radiological Physics Center in Houston (USA), etc. All the TLD intercomparisons receive the support of the BIPM, the Austrian Primary Standard Dosimetry Laboratory (BEV), and some advanced radiotherapy centers. These institutes provide reference irradiations for the TLD sets, acting as an external quality control of the Agency's TLD dosimetry service.

During 1995 the TLD postal service has distributed 425 thermoluminescence dosimeters to radiotherapy centers in developing countries for dose quality audits of photon and electron beams from Co-60 therapy units and medical accelerators. Results from 100 Co-60 beams and 134 accelerator photon and electron beams have been processed during the year. TLD dose checks of electron beams have been completed in 46 radiotherapy institutions in Europe and the USA for testing the new method and developing procedures to expand the TLD postal service routinely to electron treatment beams. Part of the work this year has been done in collaboration with the SSDLs of Argentina and India using the technology provided by the Agency.

In the future, the TLD postal service should be extended to QA procedures for brachytherapy techniques, both in high and low dose rate treatment modalities. The number of radiotherapy centers undergoing dose quality audits per year could be increased with the purchase of a TLD automatic system, and almost doubled with the allotment of one additional technical staff at the Dosimetry Laboratory; funding is being sought to allow a temporary position dedicated to these tasks. A study is in progress to evaluate the alanine-ESR dosimetry system, which is being used so successfully for the industrial applications, for therapy. The preliminary results were presented at the 4th International Symposium on ESR Dosimetry and Applications in Munich.

The follow-up of hospitals with dose check results outside the acceptance limits (larger than approximately ±5%) includes since recently a user-blind repetition of the exercise; in the past outlayers were simply informed of their deviation. The recruitment of experts travelling to the site to resolve deviations confirmed after the blind repetition is a major goal of the project to be implemented, although extra funds for this task are considerably restricted.

3.2. The IDAS programme for industrial facilities

Several guidelines and standard practices have been developed by international organisations that provide recommendations for the radiation processes, such as sterilization of medical products and food irradiation. One of the principal concerns of all the guidelines is process validation, and the key element of this is a well characterized, reliable dosimetry system that is traceable to a PSDL. To help the Member States establish such a dosimetry system in particular, and the radiation processing technology in general, the Agency established the High-Dose Dosimetry Programme in 1977. The principal ingredient of this programme has been the International Dose Assurance Service (IDAS).

The IDAS performs dose checks for the industrial facilities used for radiation processing applications. Alanine-ESR dosimeters are irradiated by the operators of the facilities using radiation doses relevant to industrial application (0.1 to 100 kGy). The reference irradiation conditions are monitored and this information forwarded to the Agency's Dosimetry Laboratory along with the dose values. The dosimeters are then analysed at the laboratory and the results compared with the stated values; a certificate is then issued stating the relative errors. IDAS thus provides an independent check on the entire dosimetry system of the participant; namely their routine and/or reference dosimeters, analysis equipment, procedure for the use of the dosimeters, any computer software being used, skill of the technical staff, etc. In case of a discrepancy that is greater than 5% advice is provided through letters as to its possible causes and then followed by another dose check.

During 1995 IDAS has distributed 68 dosimeter sets (each consisting of four dosimeters) to 20 participating institutes from 16 Member States. As per our QA programme, the annual dosimetry audit of the IDAS was conducted by the National Physical Laboratory, the PSDL of the United Kingdom. Also, the new batch of dosimeters was calibrated in our Gammacell-220, the dose rate of which is traceable to the NPL. In collaboration with the BIPM, an intercomparison for Co-60 gamma rays was organised between nine calibration laboratories. The last such exercise was held about ten years ago. The standard deviation of the population was 2.1% at 15 kGy and 2.4% at 45 kGy. The Agency value agreed with the mean value within 1% for both the dose levels.

Presently IDAS is limited to Co-60 gamma rays, however, a similar service for electron beams with energy larger than 4 MeV is being implemented in 1996 using the same transfer dosimetry system.

4. Transfer of dosimetry techniques

The transfer of dosimetry techniques is provided through coordinated research programmes (CRPs), technical co-operation projects (TCs), training courses, fellowships, seminars, symposia and publications.

The IAEA's technical cooperation programme has played a crucial role in the establishment of most SSDLs in the developing countries. Its assistance has ranged from very modest projects involving a few weeks of expert advice to large scale projects in which the IAEA has provided, over a period of several years, the training and major basic equipment for SSDLs. The distribution of the existing SSDLs shows that most countries have established an infrastructure for standardization of radiation measurements. However, additional efforts are necessary for expanding the network, especially for the African continent. The training of the staff is important also in the existing SSDLs to raise the level of performance and to extend their activities to participate in QA in radiotherapy dosimetry at hospitals.

After years of successful implementation of the SSDL network, the role of the Dosimetry Section in Agency's TC projects related to SSDLs has reached a *plateau* where support for only one or two SSDLs per year is requested; most of the activities of the Dosimetry Section in the TC field are focused into radiotherapy projects, mainly related to the physical aspects of QA programmes. These are usually performed in collaboration with the Radiotherapy Section of RIHU and the Radiological Safety Unit of NENS. It should be emphasized, however, that the degree of involvement of the Dosimetry Section in Agency's TC projects is considerably smaller than that of other Sections, as most activities of the Dosimetry Section are concentrated in providing Member States the services described above.

A Code of Practice was published on "Absorbed Dose Determination in Photon and Electron Beams" (Technical Report Series No. 277, IAEA, Vienna, 1987) which is used by most physicists involved with dosimetry in radiation therapy. This so-called *IAEA Dosimetry Protocol* has become one of the international standard dosimetry recommendations, and has also been adopted by some developed countries as their national Dosimetry Protocol. A CRP has been conducted during the last years towards the verification and comparisons with other dosimetry methods of TRS-277, providing support to the IAEA recommended procedures. A manual on "Calibration of Dosimeters Used in Radiotherapy" (Technical Report Series No. 374, IAEA, Vienna, 1994) was published mainly for SSDLs and for other similar laboratories involved in the calibration of dosimeters. A new IAEA Code of Practice for the calibration and use of parallel-plate ionization chambers in therapeutic electron and photon beams has been edited and submitted for publication. This document complements and updates the *IAEA Dosimetry Protocol* for the calibration of the clinical beams used in external radiotherapy. A CRP is planned in conjunction with the implementation of the new Code of Practice. To take into account the recent developments in the field, a new Code of Practice, based on the absorbed dose to water standard, which will replace TRS-277 is being planned for the biennium 1997-98.

An IAEA SSDL Newsletter is published periodically and distributed among the members of the SSDL network and of the scientific community. It is planned to extend the scope of the Newsletter to cover the rest of the activities of the Dosimetry Section and expand its readership also to hospital physicists and operators of the radiation processing facilities. Its distribution through the Internet-based WWW is being considered although the scientific contents of the Newsletter, as opposed to a simple bulletin of news, and specially the lack of computer staff, impose practical limitations.

Within the projects related to radiation processing facilities, a CRP on the development of quality control dosimetry techniques for particle beams has just been concluded. It accomplished its main objective: in its final meeting, it recommended that the Agency establish a transfer dosimetry system for electron beams based on alanine-ESR, organise an international intercomparison as an issuing laboratory, and extend the IDAS to electron beams ($E>4$ MeV). This recommendation is now being implemented. An additional research programme to characterize and evaluate the high dose dosimetry techniques for QA in radiation processing is being conducted with 8 institutions involved. Its objectives are to understand and evaluate the influence of various external parameters on the performance of several routine dosimeters, and to develop reference dosimetry techniques for low energy electrons ($E<4$ MeV).

A pilot study conducted to transfer quality assurance techniques to developing countries has motivated two new CRPs with 13 institutions being involved. These are addressed to the development of QA programmes for radiotherapy dosimetry in developing Member States, with the objectives of assisting in the implementation of national quality audit services in collaboration with the health ministries; and helping the SSDLs in the implementation of the standards in terms of absorbed dose to water.

Great emphasis is put also on organizing training courses and on providing fellowships. A Model Project in Latin America (Mexico), to establish a university degree (MSc and PhD) programme replacing simpler professional training in medical physics, is being implemented in parallel with other university projects supporting the education of medical physicists in Argentina, Colombia, Peru, etc. A Regional Seminar on radiotherapy dosimetry in Thailand, and a Regional

Training Course on dosimetry in brachytherapy in Mexico, have been conducted during 1995 within the budget of the Dosimetry Section.

The Dosimetry Section also collaborates with the Food Preservation Section (RIFA) and the Industrial Applications and Chemistry Section (RIPC) in organising regional workshops and training courses in the field of dosimetry for process and quality control for radiation processing.

RADIATION DOSIMETRY WITH PLANE-PARALLEL IONIZATION CHAMBERS: AN INTERNATIONAL (IAEA) CODE OF PRACTICE[1]

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Abstract

Research on plane-parallel ionization chambers since the IAEA Code of Practice (TRS-277) was published in 1987 has expanded our knowledge on perturbation and other correction factors in ionization chamber dosimetry, and also constructional details of these chambers have been shown to be important. Different national organizations have published, or are in the process of publishing, recommendations on detailed procedures for the calibration and use of plane-parallel ionization chambers. An international working group was formed under the auspices of the IAEA, first to assess the status and validity of IAEA TRS-277, and second to develop an international Code of Practice for the calibration and use of plane-parallel ionization chambers in high-energy electron and photon beams. The purpose of this work is to describe the new Code of Practice.

1. INTRODUCTION.

The advantages of using plane-parallel ionization chambers in the dosimetry of therapeutic electron beams have been recognised in all dosimetry protocols. The design characteristics, mainly regarding the shape and size of the collecting volume, make this instrument theoretically ideal for measurements in regions with large dose gradients in the beam direction.

A number of chambers are available today, a few of them having completely new designs, with practically negligible perturbation effects in electron beams. Large correction factors have been found, however, for other chambers, mainly at low electron energies. There is still controversy on the use of plane-parallel chambers for photon beam dosimetry. Most chambers are far from homogeneous in their construction as, in general, materials with different scattering and absorption

[1] Paper presented at the IAEA Seminar on "Radiotherapy Dosimetry: Radiation Dose in Radiotherapy from Prescription to Delivery", Rio de Janeiro, Brazil, 27-30 August 1994.

properties are used in the various walls. It is likely that these wall effects approximately balance other effects in electron beams, but measurements and calculations in photon beams have shown the need for correction factors to account for the different materials in the chamber. This suggests that plane-parallel chambers should mainly be used for absorbed dose determinations in electron beams but only for relative measurements in photon beams. The remaining problem is the calibration of the chamber.

The lack of details on dosimetry procedures using plane-parallel chambers, particularly regarding their calibration, i.e., a practical determination of the N_D (N_{gas}) chamber factor, has been one of the major criticisms made of the IAEA Code of Practice, TRS-277 [1] where only a reference to the procedures described by NACP [2] was made. It was considered that these procedures were well established and therefore still to be recommended. The influence of the central electrode correction for cylindrical chambers in TRS-277, however, added an unexpected complication to experimental determinations of N_D based on a comparison in electron beams [3].

Research in the field since IAEA TRS-277 was published has expanded our knowledge on perturbation and other correction factors in ion-chamber dosimetry, and also constructional details of the chambers have been shown to be important. Different national organisations have published [4, 5] or are in the process of publishing [6, 7] recommendations including detailed procedures for the use of plane-parallel chambers. An international working group was formed under the auspices of IAEA, first to assess the status and actual validity of IAEA TRS-277 [1] and second to develop an international Code of Practice for the use of plane-parallel ionization chambers in high-energy electron and photon beams. The purpose of this work is to describe the new Code of Practice. Further details on the present situation regarding correction factors and quantities briefly discussed here can be found in [3].

2. AN OVERVIEW OF THE NEW CODE OF PRACTICE.

The contents of the Code of Practice are shown in Table I. It can be observed that together with a rather conventional distribution of the different sections 1-9, Section 10 contains a summary of all the procedures and data required; this Section is effectively the Code of Practice. The report also contains Appendices where different topics are covered in detail; they also include Worksheets.

The new Code updates information in IAEA TRS-277 regarding recent developments in radiotherapy dosimetry. In most cases differences from existing values or the magnitude of new corrections, are within half a percent of unity but developments (and clarifications) in the field are taken into account. Of special interest for the calibration and use of plane-parallel ionization chambers are

- the effect of metallic central electrodes in cylindrical ionization chambers (included in TRS-277 as a global factor) has been separated into two components, one at the Co-60 calibration (k_{cel}=1.006 for a Farmer-type chamber) and therefore entering into $N_{D,air}$ [2], and another at reference measurements in a phantom (for a Farmer-type chamber p_{cel}=0.994 in Co-60; p_{cel}=0.998 in electron beams). This yields a global correction equal to 1.004 in electrons. It should be noted that cylindrical ionization chambers are used as reference instruments for the calibration of plane-parallel ionization chambers in most calibration alternatives. New values

[2] Note that the factor N_D in TRS-277 is now denoted by $N_{D,air}$ in order to distinguish it from $N_{D,w}$, the factor in terms of absorbed dose to water.

for these corrections, based on Monte Carlo calculations, are adopted [8]. The new expression for $N_{D,air}$ for cylindrical ionization chambers becomes

$$N_{D,air} = N_K (1-g)\, k_{att} k_m k_{cel} \qquad (1)$$

TABLE I. CONTENTS OF THE *IAEA CODE OF PRACTICE* FOR PLANE-PARALLEL IONIZATION CHAMBERS

1. Introduction
2. Update of the information in TRS-277
3. Equipment
4. Beam quality specification
5. N_K-based formalism and determination of $N_{D,air}$ for plane-parallel ionization chambers
6. N_{D,w,Q_o}-based formalism and determination of N_{D,w,Q_o} factors for plane-parallel ionization chambers
7. Use of plane-parallel chambers in electron beams
8. Use of plane-parallel chambers in photon beams
9. The uncertainty in absorbed dose determination at the reference depth using plane-parallel chambers in electron beams
10. A **Code of Practice** for the calibration and use of plane-parallel ionization chambers
Appendix A. Worksheets
Appendix B. Stopping-power ratios in clinical electron beams.
Appendix C. Chamber perturbation factors in electron and photon beams

- a procedure based on an absorbed-dose-to-water calibration factor, $N_{D,w}$, is also introduced. This symbol was given in TRS-277 but in practice its use was restricted to low-energy X-rays. It is now becoming available for high-energy photons. At present the most common approach is to provide users with $N_{D,w}$ at a reference quality Q_o, usually ^{60}Co, and apply beam quality correction factors for other beam qualities. Users should be warned of the possibility of confusion arising from the notation N_D used by AAPM TG-21 [9] for the $N_{D,w}$ factor.

- a new scaling procedure for conversion of depths and ranges measured in plastic to equivalent quantities in water is given; this is based on the concept of *detour factors* which is more accurate than ratios of csda ranges [10]. For ranges the scaling law is given by

$$R_{water}[cm] = R_{plastic}[cm]\,\frac{\rho_{user}}{\rho_{table}}\,C_{plastic} \qquad (2)$$

where ρ_{user} should be determined by the user. The same relation is used for scaling depths. Values of ρ_{table} and C_{pl} are tabulated for PMMA, polystyrene and other plastics commonly used in dosimetry.

- a correction for the non-medium equivalence of the chamber wall material, p_{wall}. This factor has implicitly been assumed to be unity in electron dosimetry protocols to date. There is however considerable experimental evidence that this factor may not be unity for certain plane-parallel chamber designs; the probable mechanism here is backscattering differences between the material behind the cavity and that of the phantom material. However only values for an *overall* perturbation factor $p_Q = p_{cav}\, p_{wall}$ are given; p_{cav} replaces p_u as the correction for the in-scattering effect in gas cavities.

- new calculations of stopping-power ratios water/air, $s_{w,air}$, based on a comparison of several independent Monte Carlo codes where different density effect corrections were taken into account. Compared with the stopping-power ratios in TRS-277, differences are small for the electron energies most commonly used in radiotherapy, being close to 0.5% at most depths. The recommendation for the small change is justified in terms of the lack of ambiguity in the corrections used and the higher accuracy of the present set of data.

- the determination of the recombination correction factor for plane-parallel ionization chambers using the "two-voltage" method has been shown to have limitations for most chambers due to the lack of linearity of saturation curves in the region of interest. In order to decrease the influence in the dosimetry procedure it is recommended to use the same voltage ratio for the determination of $N_{D,air}$ and for the absolute dose determination.

Section 3 provides a detailed description on phantoms and equipment available, with emphasis on the properties of plane-parallel ionization chambers both for electron and photon radiation. Chambers of new design (Attix, Roos, etc) are included in the compilation. As in TRS-277, water is the recommended reference medium although plastics may be used for measurements at low electron energies. Emphasis is given, however, to the high accuracy achievable today with modern equipment in positioning ionization chambers in water phantoms which thus reduces the need to use plastic phantoms.

The uncertainty in absorbed dose determination at the reference point using the recommended procedure for determining $N_{D,air}$ is treated in detail, separating the different steps of the dosimetric procedure in a similar way to TRS-277 but incorporating an updated evaluation of uncertainties in the different steps. Uncertainties are also evaluated for the alternative calibration methods based on measurements in photon beams.

Further details on certain sections follow.

2.1. Beam quality specification

The specification of the quality of the beams used for the calibration of plane-parallel ionization chambers follows the recommendations given in TRS-277. As mentioned in the introduction, absolute dosimetry is to be performed in electron beams only, as is the recommended calibration procedure (see below).

For dosimetry purposes it has become customary to specify the quality of electron beams in terms of the mean energy at the surface of the phantom, E_o, determined from empirical relationships between electron energy and the 50% range in water, R_{50}. $\bar{E}_o$ is needed for the selection of different quantities and parameters in the formalism, and mainly affects the choice of stopping-power ratios water to air, $s_{w,air}$, at the reference depth, namely $s_{w,air}(\bar{E}_o, z_{ref})$. As in IAEA TRS-277 [1] and most dosimetry protocols, the recommendation is to determine $\bar{E}_o$ using the energy-range relationship

$$\bar{E}_o = C\,R_{50} \qquad (3)$$

where C=2.33 MeV cm^{-1} and R_{50} is obtained from a depth-dose distribution measured with constant source-chamber distance. As is well known, when the dose distribution has been obtained with a constant source-surface distance (SSD=100 cm) Eq. (3) is not strictly valid. As an alternative IAEA TRS-277 has provided tabulated data for determining $\bar{E}_o$ either from ionization curves measured at SSD=100 cm with an ionization chamber or from depth-dose distributions at SSD=100 cm, measured for instance with solid state detectors. These data can be fitted with the following second order polynomial:

$$\bar{E}_o = 0.818 + 1.935\,R_{50}^J + 0.040\,(R_{50}^J)^2 \qquad (4)$$

for R_{50}^J determined from a depth-ionization curve and

$$\bar{E}_o = 0.656 + 2.059\,R_{50}^D + 0.022\,(R_{50}^D)^2 \qquad (5)$$

for the case of a depth-dose curve, R_{50}^D. For energies above 3 MeV, Eqs. (4) and (5) yield stopping-power ratios, water-to-air, that on the average agree within 0.2% up to depths equal to 0.80 R_p with $s_{w,air}$ values obtained with $\bar{E}_o$ derived from TRS-277 Table IV, with a maximum deviation of 0.4% close to 12 MeV.

Although improved energy-range relationships between $\bar{E}_o$ and R_{50}, based on Monte-Carlo calculations for mono-energetic electron beams, have been developed [3, 11], all yield $\bar{E}_o$ values higher than the above expression. This would result in lower stopping-power ratios at the reference depth compared to those obtained with $s_{w,air}(\bar{E}_o, z_{ref})$ and $\bar{E}_o$ from Eq. (3).

2.2. Determination of $N_{D,air}$ for plane-parallel chambers

Several different methods have been proposed by Mattsson *et al* [12] for obtaining the absorbed-dose-to-air chamber factor $N_{D,air}$ for a plane-parallel chamber. These methods fall into two broad categories. In the first one, a Standards Laboratory calibrates the chamber in terms of N_K and then $N_{D,air}$ is obtained theoretically.

In the second one, the user determines $N_{D,air}$ directly by experimental intercomparison with a reference ion-chamber having a known $N_{D,air}$ factor. Both chambers are alternatively positioned at a reference depth in a phantom and the unknown $N_{D,air}$ is obtained from equating the absorbed doses with the two chambers. These procedures have been extensively discussed in Ref. [13] and in the recent TG-39 protocol of the AAPM [14]. Methods in the second category are generally performed in the user's beam, either ^{60}Co or high-energy electrons [12]. It can be noted that this method can in principle be applied to determining $N_{D,air}$ for any chamber that is to be used in electron or photon beams e.g. a second cylindrical chamber provided that $N_{D,air}$ is already known for a reference chamber [4, 15]. Consequently the chamber to be calibrated (not necessarily plane-parallel) and the reference chamber will be denoted by x and *ref* respectively.

The primary recommendation is the use of a high-energy electron beam. Following the formalism in TRS-277, and equating the absorbed dose at the reference depth with the two chambers, the expression for $N_{D,air}$ for the chamber x to be calibrated, becomes

$$N^{x}_{D,air} = N^{ref}_{D,air} \frac{M^{ref}}{M^{x}} \frac{p^{ref}_{wall} p^{ref}_{cav} p^{ref}_{cel}}{p^{x}_{wall} p^{x}_{cav} p^{x}_{cel}} \qquad (6)$$

where the numerator and denominator correspond to the D_w determination using the reference chamber (usually cylindrical) and chamber x respectively, and the stopping-power ratios cancel out. M^{ref} and M^{x} are ratios of the readings of the two chambers to those of an external monitor to take into account possible accelerator output fluctuations. They must be corrected for the polarity effect, for recombination, and for temperature and pressure. Note that p^{ref}_{wall} for the reference chamber is unity as recommended reference cylindrical chambers are assumed to have negligible wall effects in electron beams [16, 17]. For most plane-parallel ionization chambers and at the energies recommended for the calibration, the product of the factors p^{x}_{cav} and p^{x}_{wall} are practically unity. The factor p^{x}_{cel} is not relevant for plane-parallel ionization chambers but as the procedure can also be extended to cylindrical ion chambers it has been retained in this Equation. For the case of x being a cylindrical chamber the value of p^{x}_{cav} should be interpolated from the data from Johansson *et al* [16] given in TRS-277 Table XI..

The phantom material should preferably be the same as that used for the absolute dose determination. This automatically ensures that the overall effects of any perturbation due to differences in backscattering between the material behind the cavity and that of the phantom (i.e. the component of p_Q due to p_{wall}) will be minimized. Water is the preferred material. The energy of the electron beam should be as high as possible in order to minimise the perturbation due to the air cavity of the reference chamber. As a guide p^{ref}_{cav} should be within 2% of unity. For a cylindrical reference chamber with an internal radius of 3 mm (approximately Farmer type) this means that $\bar{E}_o$ should be no lower than 15 MeV but should preferably be as high as possible; the lower limit on $\bar{E}_o$ may be lowered if the chamber radius is smaller. The depth should be the same as the reference depth z_{ref} used for absorbed dose determination in the chosen high-energy beam. The SSD should be 100 cm and the field size should be approximately 12 cm x 12 cm or larger - this is not critical. The chambers are to be placed with their respective effective points of measurement, P_{eff}, at the same depth. A Farmer-type chamber, i.e. approximately 6 mm internal diameter and 1 mm electrode diameter, for the reference cylindrical chamber is recommended here as a great deal of experience has been gained with such chambers and the correction factors can be said to be well known [18, 19]. The choice of a chamber with a radically different geometry, e.g. a very thick central electrode, can lead to larger uncertainties.

Alternative methods for obtaining the absorbed-dose-to-air chamber factor $N_{D,air}$ for a plane-parallel chamber based on measurements made in a ^{60}Co beam have been introduced. They are classified into two categories generally depending on the institution where the calibration is performed. The *in-phantom* method is generally performed in the user's beam at the Hospital, although it can also be performed at the Standards Laboratory. Measurements free in air are usually performed in a ^{60}Co beam at the Standards Laboratory.

The calibration in a ^{60}Co beam at depth in a phantom has been described by several authors, first by Mattsson *et al* [12] and then in more detail by Attix [20]. The approach is based upon the determination of $N_{D,air}$ from the knowledge of the absorbed dose in the phantom determined with a calibrated reference chamber, like that recommended in the electron-beam method, but in this case irradiated with a ^{60}Co beam. The formalism yields:

$$N_{D,air}^{pp} = N_{D,air}^{ref} \frac{M^{ref}}{M^{pp}} \frac{p_{wall}^{ref} p_{cel}^{ref}}{p_{wall}^{pp}} \quad (7)$$

where p_{wall}^{ref} and p_{cel}^{ref} are perturbation factors of the reference chamber at ^{60}Co; p_{cel}^{ref} is unity for a graphite electrode and 0.994 for a Farmer-type chamber. The standard SSD for a ^{60}Co unit and a field size of 10 cm x 10 cm at the surface should be used. In this method the effective point of measurement for both chambers should be placed at a reference depth of 5 g cm^{-2} in a phantom that matches the plane-parallel chamber material (to minimise p_{wall}^{pp}) or in water if the p_{wall}^{pp} factor is known. For cylindrical chambers in ^{60}Co beams P_{eff} is positioned at a distance equal to 0.6 r from the centre of the chamber.

It is important to note that when a non-water phantom is used, TRS-277 does not provide a direct determination of the perturbation p_{wall} at ^{60}Co as absorbed dose should only be determined in a water phantom. The perturbation factor of the reference chamber is determined according to the general equation that takes into account the thin waterproofing plastic or rubber sleeve normally used to protect the chamber in a water phantom (see also Refs. [21, 22]):

$$p_{wall}^{ref} = \frac{\alpha\, s_{wall,air}\, (\mu_{en}/\rho)_{med,wall} + \tau\, s_{sleeve,air}\, (\mu_{en}/\rho)_{med,sleeve} + (1-\alpha-\tau)\, s_{med,air}}{s_{med,air}} \quad (8)$$

where *med* is the phantom material and α and τ the fractions of ionization due to electrons arising from the wall and waterproofing sleeve respectively. A fit to the available data for α [23] is given. By applying this fit to the combined thickness of the wall and the sleeve, and subtracting α_{wall} from this, an expression for τ is obtained. This insures that $\alpha+\tau^2 \leq 1$.

The perturbation factor p_{wall}^{pp} in ^{60}Co beams is the major source of uncertainty in this procedure and the reason why the electron-beam method for the calibration of plane-parallel ionization chambers is the preferred option in the new Code of Practice. Differences in p_{wall}^{pp} close to 2% have been reported, either between Monte-Carlo calculations and experimental data [24], or due to chamber-to-chamber variations for chambers of the same type (from the same or from different manufacturers) [25]. It has to be emphasised that p_{wall}^{pp} depends on the phantom material used for the calibration.

The calibration-in-air method is similar to the free-in-air approach used with cylindrical chambers in Standard Laboratories. The air-kerma rate, free in air, must be known at the position of the cavity centre and N_K of the plane-parallel ionization chamber is then determined. The plane-parallel ionization chamber with appropriate build-up material is placed free in air in a ^{60}Co beam, with its center positioned at the point where K_{air} is known. The build-up material should have the same outer dimensions as the chamber and preferably be of the same material as the predominant material of which the chamber is constructed. The procedure yields the N_K calibration factor of the plane-parallel chamber

$$N_K^{pp} = \frac{K_{air}}{M^{pp}} \quad (9)$$

and if the product $k_{att}\, k_m$ is known $N_{D,air}$ is determined according to the well-known expression

$$N_{D,air}^{pp} = N_K (1-g)\, k_{att} k_m \quad (10)$$

where for plane-parallel ionization chambers k_{cel} is not involved. In principle this procedure is used together with a *universal* value of $k_{att}\, k_m$ for a given type of plane-parallel ionization chamber. The limitations of this approach increase considerably the estimated uncertainty because k_m is not well known.

2.3. Determination of $N_{D,w}$ for plane-parallel chambers

The formalism for the determination of absorbed dose to water in photon and electron beams using a $N_{D,w}$-based calibration factor has been given in detail by Hohlfeld [26]. The absorbed dose to water at the reference point of the chamber (where the calibration factor applies) in a phantom irradiated by a beam of reference quality Q_o is given by the simple relationship

$$D_{w,Q_o} = M_{Q_o}\, N_{D,w,Q_o} \qquad (11)$$

where $N_{D,w,Qo}$ is obtained at the Standard Laboratory from the knowledge of the standard quantity absorbed dose to water at the point of measurement in water for the calibration quality Q_o.

Efforts are at present being addressed to providing $N_{D,w,Q}$ calibrations for photon beams, mainly ^{60}Co gamma-rays and to a lesser extent high-energy photon and electron beams [27-31]. A practical approach in common use is to provide users with $N_{D,w,Co}$, i. e. calibration at the reference quality ^{60}Co, and apply *beam quality* correction factors k_Q for other beam qualities [26, 32]. For beams other than the reference quality the absorbed dose to water is then given by

$$D_{w,Q} = M_Q\, N_{D,w,Q_o}\, k_Q \qquad (12)$$

where the factor k_Q corrects for the difference between the reference beam quality Q_o and the actual quality being used, Q. k_Q should ideally be determined experimentally at the same quality as the user's beam, although this is seldom achievable. When no experimental data are available an expression for k_Q can be derived comparing Eq. (11) with the formalism in TRS-277; this ensures consistency with the $N_{D,air}$ procedure as k_Q is calculated with the data in TRS-277 [26, 33, 34]. In therapeutic electron and photon beams the general assumption of $(W_{air})_Q=(W_{air})_{Qo}$ yields the equation for k_Q

$$k_Q = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_o}} \frac{p_Q}{p_{Q_o}} \qquad (13)$$

which depends only on ratios of stopping-power ratios and perturbation factors. It should be noted that the chamber-dependent correction factors k_{att}, k_m and k_{cel} are not involved in the definition of k_Q. The only chamber specific factors involved are the perturbation correction factors p_Q and p_{Q_o}.

The connection between the $N_{D,air}$ and the $N_{D,w}$ based formalisms is established by the relationship,

$$N_{D,w,Q} = N_{D,air}(s_{w,air})_Q\, p_Q \qquad (13)$$

In principle Eq. (13) could be used to determine $N_{D,air}$ independent of the factors k_{att}, k_m and k_{cel}.

The use of ^{60}Co as reference quality for determining N_{D,w,Q_o} for plane-parallel ionization chambers is an attractive possibility, especially for most SSDLs. Using the formalism at other qualities (both high-energy electron and photon beams) requires, however, the knowledge of p_{Q_o} at ^{60}Co in Eq. (12) which enters in k_Q; this is the main drawback of this procedure. This is also the case for the alternative option which enables users to determine N^{pp}_{D,w,Q_o} directly by experimental intercomparison in a ^{60}Co beam with a reference ion-chamber (cylindrical in this case, where p_Q is more precisely known) having a known N^{ref}_{D,w,Q_o} factor.

It is assumed that the water absorbed dose rate is known at 5 cm depth in a water phantom for ^{60}Co gamma rays. The plane-parallel chamber is placed with its reference point at a depth of 5 cm in a water tank where the absorbed dose to water D_w is known and $N^{pp}_{D,w,Co}$ obtained from

$$N^{pp}_{D,w,Co} = \frac{D_w}{M^{pp}} \tag{14}$$

D_w is obtained using a reference chamber having a calibration factor $N^{ref}_{D,w,Co}$. The calibration factor for the plane-parallel chamber becomes

$$N^{pp}_{D,w,Co} = N^{ref}_{D,w,Co} \frac{M^{ref}}{M^{pp}} \tag{15}$$

where it is assumed that the centre of the reference chamber is positioned at the depth of measurement. The alternative use of P_{eff} is also a valid option. All experimental conditions are identical to those for the determination of $N_{D,air}$ in ^{60}Co using in-phantom measurements.

2.4. Use of plane-parallel chambers

The use of plane-parallel ionization chambers both in electron and in photon beams is considered in line with the introduction above.

2.4.1. Reference conditions

In electron beams, reference conditions consider a reference depth z_{ref} (as in TRS-277) instead of the depth of maximum absorbed dose used in other dosimetry protocols. The absorbed dose to water is determined according to

$$D_w(z_{ref}) = M_u\, N_D\, s_{w,air}\, p_Q \tag{16}$$

where

$$p_Q = p_{cav}\, p_{wall} \tag{17}$$

Note that the perturbation factor p_u in TRS-277 is replaced here by p_Q which is the product of two factors (Eq. (17)). The first, p_{cav}, is the electron fluence perturbation factor, identical to the p_u factor in TRS-277 Table XI. The change in symbol attempts to emphasise that it is exclusively concerned with effects due to the air cavity, rather than the wall material, that is, a correction for the effect known as *in-scattering* where electron tracks are scattered by the medium towards the air cavity. It is stressed that p_{cav} is strictly known at the reference depth only. The second factor p_{wall} takes into account the lack of backscatter of the back wall material compared to water, and has implicitly been assumed to be unity in electron dosimetry protocols to date. This factor is discussed in detail in Appendix C. It was not possible to make definitive recommendations regarding p_{wall} due to the present lack of consensus in the literature [35, 36]. However, all experimental determinations of perturbation in plane-parallel ionization chambers have effectively been of the overall factor p_Q. Figure 1 shows the values recommended for various plane-parallel chambers in the new Code of Practice.

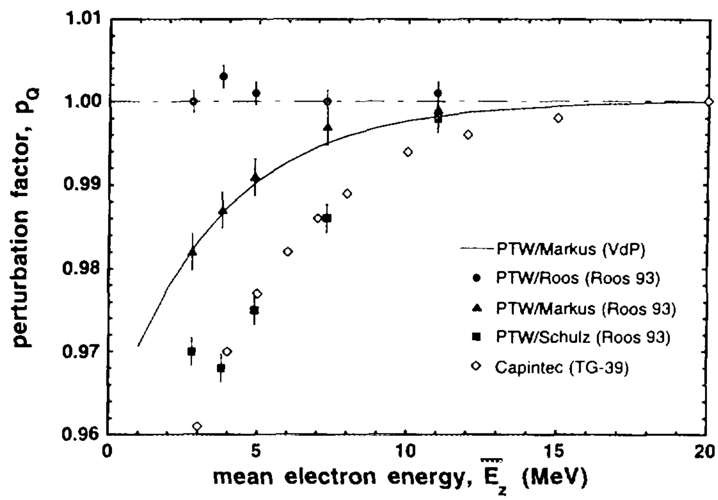

FIG. 1. The variation of the perturbation factor p_Q for several different plane-parallel chambers in common use, relative to the NACP chamber, indicated by the dashed line drawn at $p_Q = 1.00$. All the measurements were made at the depth of dose maximum and normalized to the quotient test chamber/NACP in a high-energy electron beam. The full line is a fit to 3 separate measurement series on different accelerators using the PTW/Markus chamber [37]. *The filled data points are measurements on three different PTW designs taken from* [38], *and re-normalized so that $p_Q = 1$ for the NACP chamber; the unfilled symbols are for the Capintec-PS-033 chamber as given in* [14].

Regarding water/air stopping-power ratios, new calculations have been performed [39] including the two sets of density-effect in water given in the ICRU-37 electron stopping power tables. They are density-effect corrections according to the Sternheimer's model and the more accurate calculations of Ashley based on semi-empirical dielectric-response functions (DRF). It was argued [39] that for electron energies used in radiotherapy, where the density effect in air is negligible, δ_{DRF}-based water/air stopping-power ratios provide a more accurate set of data. Differences in stopping-power ratios due to the different evaluations of the density effect correction are within 1%. The information on the density-effect correction in the set of values actually in use in TRS-277 and in other dosimetry protocols is, however, ambiguous. A new set of data is provided here based on Ashley density-effect corrections for water, Table II.

TABLE II. SPENCER-ATTIX STOPPING-POWER RATIOS (Δ=10 KeV), WATER TO AIR ($s_{w,air}$) FOR ELECTRON BEAMS AS A FUNCTION OF $\bar{E}_o$ AND DEPTH IN WATER. Density effect correction (δ_{Ashley}) and I-values from ICRU-37 and electron fluence Monte Carlo calculations from Andreo [39] using the EGS4 Monte Carlo system.

depth in water(mm)	Electron beam energy $\bar{E}_o$																			
	1 MeV	2 MeV	3 MeV	4 MeV	5 MeV	6 MeV	7 MeV	8 MeV	9 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV	22 MeV	25 MeV	30 MeV	40 MeV	50 MeV
R_p (mm)*	3.6	8.8	14.0	19.1	24.3	29.4	34.5	39.6	44.7	49.8	59.9	69.9	79.9	89.8	99.6	109.3	123.8	147.7	194.1	238.8
0	1.117	1.088	1.066	1.049	1.034	1.026	1.014	1.006	0.998	0.993	0.981	0.969	0.961	0.955	0.948	0.943	0.936	0.924	0.912	0.907
1	1.125	1.096	1.072	1.055	1.040	1.030	1.018	1.010	1.002	0.996	0.985	0.973	0.965	0.959	0.951	0.946	0.938	0.927	0.914	0.908
2	1.131	1.104	1.079	1.060	1.045	1.033	1.022	1.014	1.005	0.999	0.988	0.976	0.968	0.962	0.954	0.948	0.941	0.929	0.915	0.909
3	1.134	1.111	1.085	1.065	1.049	1.037	1.026	1.018	1.009	1.002	0.990	0.979	0.971	0.964	0.957	0.951	0.943	0.932	0.917	0.911
4	1.136	1.117	1.091	1.070	1.053	1.041	1.029	1.021	1.011	1.005	0.993	0.982	0.973	0.966	0.959	0.953	0.945	0.934	0.918	0.912
5		1.123	1.097	1.075	1.057	1.044	1.032	1.023	1.014	1.007	0.995	0.984	0.975	0.968	0.961	0.955	0.946	0.935	0.920	0.913
6		1.127	1.102	1.079	1.061	1.048	1.035	1.026	1.016	1.009	0.997	0.986	0.977	0.970	0.963	0.957	0.948	0.937	0.921	0.914
8		1.132	1.112	1.089	1.069	1.055	1.041	1.031	1.021	1.013	1.001	0.989	0.980	0.973	0.966	0.960	0.951	0.940	0.924	0.916
10		1.135	1.120	1.098	1.077	1.062	1.047	1.036	1.025	1.018	1.004	0.992	0.983	0.975	0.969	0.962	0.953	0.943	0.926	0.918
12			1.127	1.107	1.086	1.070	1.054	1.042	1.030	1.022	1.008	0.995	0.985	0.978	0.971	0.964	0.956	0.945	0.928	0.920
14			1.132	1.116	1.095	1.079	1.061	1.048	1.035	1.027	1.011	0.998	0.988	0.981	0.973	0.966	0.958	0.947	0.930	0.922
16			1.135	1.123	1.104	1.087	1.069	1.054	1.041	1.031	1.015	1.001	0.991	0.983	0.975	0.969	0.960	0.948	0.932	0.923
18			1.137	1.129	1.112	1.095	1.076	1.061	1.047	1.037	1.018	1.004	0.994	0.986	0.977	0.971	0.962	0.950	0.933	0.924
20				1.133	1.118	1.103	1.084	1.068	1.053	1.042	1.023	1.008	0.997	0.988	0.980	0.973	0.964	0.952	0.935	0.925
25					1.128	1.120	1.102	1.086	1.069	1.056	1.034	1.016	1.004	0.994	0.986	0.978	0.969	0.956	0.938	0.928
30					1.133	1.131	1.118	1.103	1.086	1.072	1.047	1.027	1.012	1.002	0.992	0.984	0.974	0.960	0.941	0.931
35						1.132	1.129	1.118	1.102	1.087	1.060	1.038	1.021	1.008	0.998	0.989	0.978	0.964	0.944	0.933
40								1.128	1.116	1.103	1.074	1.050	1.031	1.016	1.005	0.996	0.984	0.969	0.948	0.935
45								1.130	1.127	.1.115	1.088	1.062	1.041	1.026	1.012	1.002	0.990	0.973	0.951	0.938
50										1.125	1.102	1.075	1.053	1.035	1.021	1.009	0.995	0.978	0.955	0.940
55										1.127	1.114	1.088	1.065	1.045	1.029	1.016	1.001	0.983	0.959	0.943
60										1.124	1.123	1.100	1.077	1.056	1.038	1.024	1.007	0.987	0.962	0.946
70											1.122	1.120	1.099	1.078	1.058	1.041	1.021	0.998	0.969	0.952
80												1.118	1.118	1.099	1.078	1.060	1.037	1.009	0.977	0.957
90													1.114	1.116	1.099	1.079	1.053	1.022	0.984	0.963
100															1.114	1.098	1.071	1.036	0.993	0.970
120																1.109	1.104	1.065	1.012	0.984
140																		1.095	1.034	0.999
160																		1.099	1.058	1.015
180																			1.081	1.033
200																			1.091	1.053
220																				1.071
240																				1.084

* $R_p = -1.65 + 5.23\ E_p - 0.0084\ E_p^2$, average from Monte Carlo calculations for monoenergetic electrons using the EGS4 and ITS3 systems

Compared with the stopping-power ratios in TRS-277 differences are negligible for the most commonly used range of electron energies in radiotherapy, being close to 0.5% at most depths and high-energies (see figure 2). The small change is justified in terms of the lack of ambiguity in the corrections used and higher accuracy of the present set of data. It is interesting to note that if the comparison is made with Sternheimer-based electron stopping-powers, differences would be larger at shallow depths (up to -1.0 % for most energies) and slightly smaller at depths beyond 0.2 r_0.

As already mentioned, the specification of the "quality" of the electron beam in terms of the mean electron energy at the phantom surface is based on the "2.33 approximation", and stopping-power ratios selected with $s_{w,air}(E_o,z)$ using data from monoenergetic beams. The validity of these two approximations and their limitations is discussed in detail in Appendix B. In particular the influence of electron and photon contamination is demonstrated, showing maximum discrepancies up to 1% at z_{ref} between the $s_{w,air}(E_o,z)$ method and full Monte Carlo simulations. Differences are usually larger at shallow depths due to the difference in slope of the $s_{w,air}(z)$ distributions obtained with the two methods and increase further if analytic expressions yielding $\bar{E}_o$ values larger than the "2.33 approximation" are used [3].

It is emphasized that no accurate method exists today to predict the dependence of $s_{w,air}(z)$ on the contamination of the beam unless a full Monte Carlo simulation of the complete accelerator treatment head is performed. On the other hand, the appendix on stopping-power ratios also describes two new methods recently proposed that, used in combination, could perhaps overcome the limitations described above.

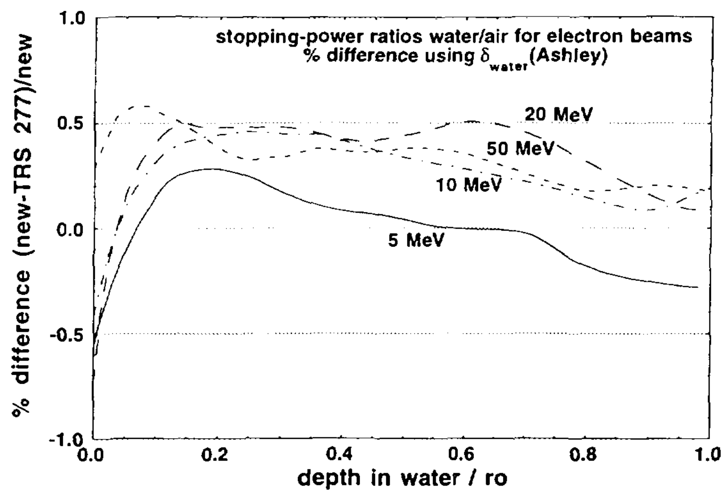

FIG. 2. Percent difference between the new stopping-power ratios for electron beams, $s_{w,air}$, given in Table II and those tabulated by TRS-277 [1] and other dosimetry protocols.

2.4.2. Non-reference conditions

Emphasis is given to the use of plane-parallel ionization chambers in non-reference conditions, especially to determine relative dose distributions.

For electron beams the need to take into account the depth variation of different quantities and correction factors for ion chamber measurements is stressed. This is a significant disadvantage compared with other detectors like TLD, diodes, plastic scintillators, synthetic diamonds, Fricke dosimeters or liquid ion chambers.

A common mistake in the application of TRS-277 for field sizes smaller than the reference field is to determine R_{50} for such fields and use equation (2) or alternative tables to determine $\bar{E}_0$, and then use $s_{w,air}(E_o,z)$ to select stopping-power ratios. As in TRS-277 it should be emphasized here that the validity of equations (2-4) or alternative tables is restricted to large field sizes. Users should be aware that stopping-power ratios are almost independent of field size, see Figure 3, and using the incorrect approach just described to determine $\bar{E}_0$ will result in stopping-power ratios that correspond to a beam with a different energy.

In photon beams, plane-parallel ionization chambers are not recommended for absolute determinations, but for relative measurements on the central axis only and for output factors. Perturbation factors in photon beams are very sensitive to the details of the construction of a chamber and they cannot be predicted with an acceptable uncertainty. Furthermore, small changes from chamber to chamber in the manufacturing process render invalid the use of "general" factors for chambers of the same make. Plane-parallel ionization chambers should be avoided in very narrow beams such as those used in stereotactic procedures.

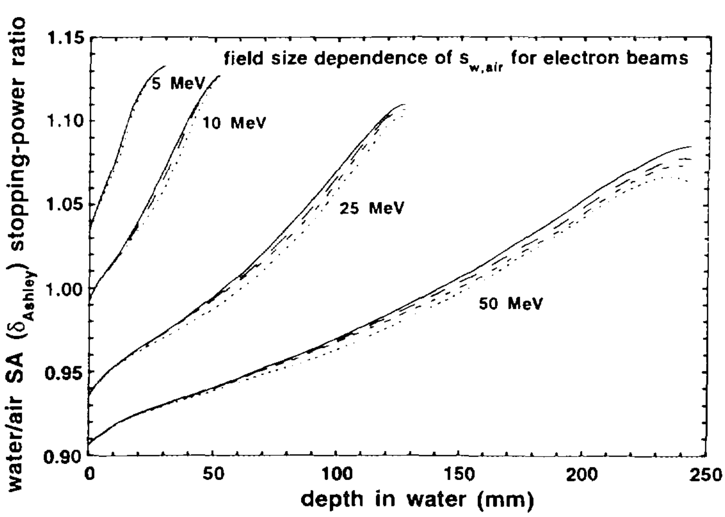

FIG. 3. Field-size dependence of water/air stopping-power ratios for electron beams determined with Monte-Carlo calculations. Radii shown in the figure are: for 5 MeV, 10 mm and broad beam; for 10 MeV, 10 mm, 20 mm and broad beam; for 25 MeV, 10 mm, 30 mm, 50 mm and broad beam; for 50 MeV, 10 mm, 40 mm, 60 mm and broad beam. The solid curves pertain to the broad beams.

3. TESTING of THE NEW CODE

Tests at two different levels have been proposed to the IAEA by the working group:

- Category A - for checking that the Code is clearly written so that the procedure can be unambiguously carried out from a practical point of view. A comparison with absorbed dose determinations using TRS-277 will be included in this category. The group includes the (obvious) α-test by the authors followed by β-tests performed by independent persons. This category must be carried out before the new Code is published and it should not take more than two months. It should be undertaken by hospital physicists in several centres, some of which should not be in an English-speaking country.

- Category B - for testing that the correct absorbed dose to water is obtained by following the new Code of Practice. This category is a longer term project and represents a significant research project to be undertaken in a sophisticated centre or centres.

4. CONCLUSIONS

The new IAEA Code of Practice for plane-parallel ionization chambers should improve the accuracy of electron beam dosimetry and, to a lesser extent, of photon beam dosimetry too. Whereas efforts have been made to incorporate the latest developments in ionization chamber dosimetry, the verification of the Code will show if they are to be preferred to previous methods or to procedures recommended in other recent protocols in the same field. It is hoped that changes in structure, compared with TRS-277, will facilitate the use of the Code.

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Cylindrical ionization chamber	cavity length (mm)	cavity radius (mm)	Wall material	t_{wall} (g/cm^2)	Build-up cap material	t_{cap} (g/cm^2)	central electrode material	k_m k_{att}
Capintec 0.07 cm^3 PR-05P mini	5.5	2.0	C-552	0.220	polystyrene	0.598	N/A	0.991
Capintec 0.14 cm^3 PR-05 mini	11.5	2.0	C-552	0.220	polystyrene	0.598	N/A	0.991
Capintec 0.65 cm^3 PR-06C Farmer type	22.3	3.2	C-552	0.050	C-552	0.924	N/A	0.990
Capintec 0.65 cm^3 PR-06C Farmer type	22.3	3.2	C-552	0.050	polystyrene	0.537	N/A	0.977
Capintec 0.65 cm^3 PR-06C Farmer type	22.3	3.2	C-552	0.050	PMMA[a]	0.547	N/A	0.983
Capintec 0.60 cm^3 PR-05P AAPM	23.8	3.3	graphite	0.046	PMMA	0.625	N/A	0.978
Exradin 0.5 cm^3 A2 Spokas (2 mm build-up)	11.4	4.8	C-552	0.176	C-552	0.352	C-552	0.992
Exradin 0.5 cm^3 A2 Spokas (4 mm build-up)	11.4	4.8	C-552	0.176	C-552	0.704	C-552	0.982
Exradin 0.5 cm^3 T2 Spokas	11.4	4.8	A-150	0.114	A-150	0.455	A-150	0.950
Exradin 0.05 cm^3 Tl min Shonka	5.7	2.0	A-150	0.114	A-150	0.455	A-150	0.956
Exradin 0.65 cm^3 Al2 Farmer type	24.2	3.1	C-552	0.088	C-552	0.493	C-552	0.997
Far West Tech 0.1 cm^3 IC-18	9.5	2.3	A-150	0.183	A-150	0.386	A-150	0.956
FZH 0.4 cm^3 TK 01 waterproof	12	3.5	Delrin	0.071	Delrin	0.430	N/A	0.978
NE 0.20 cm^3 2515	7.0	3.0	Tufnol	0.074	PMMA	0.543	aluminium	0.968
NE 0.20 cm^3 2515/3	7.0	3.2	graphite	0.066	PMMA	0.543	aluminium	0.978
NE 0.20 cm^3 2577	8.3	3.2	graphite	0.066	Delrin	0.552	aluminium	0.982
NE 0.6 cm^3 Farmer 2505 '54-'59[b]	24.0	3.0	Tufnol	0.075	PMMA	0.415	aluminium	0.973
NE 0.6 cm^3 Farmer 2505 '59-'67[b]	24.0	3.0	Tufnol	0.075	PMMA	0.545	aluminium	0.971
NE 0.6 cm^3 Farmer 2505/A '67-'74[b]	24.0	3.0	nylon 66	0.063	PMMA	0.545	aluminium	0.962
NE 0.6 cm^3 Farmer 2505/3, 3A '71-'79[b]	24.0	3.2	graphite	0.065	PMMA	0.551	aluminium	0.981
NE 0.6 cm^3 Farmer 2505/3, 3B '74-present[b]	24.0	3.2	nylon 66	0.041	PMMA	0.551	aluminium	0.965
NE 0.6 cm^3 Farmer 2571 graphite/Al cel	24.0	3.2	graphite	0.065	Delrin	0.551	aluminium	0.985
NE 0.6 cm^3 Farmer 2571 graphite/graphite cel[c]	24.0	3.15	graphite	0.065	Delrin	0.551	graphite	0.985
NE 0.6 cm^3 Farmer 2571 graphite/graphite cel[c]	24.0	3.15	graphite	0.065	graphite	0.380	graphite	0.992
NE 0.6 cm^3 Robust Farmer 2581	24.0	3.2	A-150	0.040	PMMA	0.584	aluminium	0.966
NE 0.6 cm^3 Robust Farmer 2581	24.0	3.2	A-150	0.041	polystyrene	0.584	aluminium	0.959
NE 0.325 cm^3 NPL Sec Std 2561 (cel hollow)	9.2	3.7	graphite	0.090	Delrin	0.600	aluminium	0.979

Cylindrical ionization chamber	cavity length (mm)	cavity radius (mm)	Wall material	t_{wall} (g/cm^2)	Build-up cap material	t_{cap} (g/cm^2)	central electrode material	k_m k_{att}
PTW 0.1 cm^3 23323 micro	12	1.75	PMMA	0.208	PMMA	0.357	aluminium	0.974
PTW 1.0 cm^3 23331 rigid	22	3.95	PMMA	0.060	PMMA	0.345	aluminium	0.974
PTW 0.3 cm^3 23332 rigid	18	2.5	PMMA	0.054	PMMA	0.357	aluminium	0.975
PTW 0.6 cm^3 30001 acrylic/Al cel Farmer	23	3.05	PMMA	0.045	PMMA	0.541	aluminium	0.972
PTW 0.6 cm^3 30002 graphite/graphite cel Farmer	23	3.05	graphite	0.079	PMMA	0.541	graphite	0.982
PTW 0.6 cm^3 30004 graphite/Al cel Farmer	23	3.05	graphite	0.079	PMMA	0.541	aluminium	0.982
PTW 0.125 cm^3 31002 flexible	6.5	2.75	PMMA	0.079	PMMA	0.357	aluminium	0.973
PTW 0.3 cm^3 31003 flexible	16.3	2.75	PMMA	0.079	PMMA	0.357	aluminium	0.974
Victoreen 0.1 cm^3 Radocon II 555	4.3	2.5	Delrin	0.529	N/A	N/A	N/A	0.979
Victoreen 0.3 cm^3 Radocon III 550	23.0	2.4	polystyrene	0.117	PMMA	0.481	N/A	0.965
Victoreen 0.30 cm^3 30-348	18.0	2.5	PMMA	0.060	PMMA	0.360	N/A	0.975
Victoreen 0.60 cm^3 30-351	23.0	3.05	PMMA	0.060	PMMA	0.360	N/A	0.975
Victoreen 1.00 cm^3 30-349	22.0	4.0	PMMA	0.060	PMMA	0.360	N/A	0.974
Victoreen 0.4 cm^3 30-361	22.3	2.35	PMMA	0.144	PMMA	0.360	N/A	0.976
SSI graphite[c]	17.9	4.0	graphite	0.084	graphite	0.384	graphite	0.989
SSI A-150[c]	17.9	4.0	A-150	0.056	A-150	0.373	A-150	0.955

[a] PMMA is known also as Acrylic, Lucite or Polymethylmetacrylate

[b] Year of manufacture.

[c] Experimental device, not commercially available

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TRAINING COURSE

Regional Training course on Quality Assurance in Radiation Therapy Dosimetry

Place: Manila, Philippines. Date: October 7 - 25, 1996.

Organizers: IAEA in co-operation with the government of the Philippines.

Participation: The course is open for 25 participants from IAEA Member States in the Asia and Pacific region. The participants should be currently clinical active medical physicists.

Topics: Radiotherapy in treatment of tumours

ICRU recommendations; volumes and doses

Radiotherapy equipment

Physical dosimetry

Clinical dosimetry

Quality control in treatment planning

Equipment quality control theory and practice.

International lecturers:

Dr. Torsten Landberg, Sweden

Dr. Edith Briot, France

Dr. Ben Mijnheer, The Netherlands

Dr. Jim Cramb, Australia

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