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Calibration of Reference Dosimeters for External Beam Radiotherapy

In collaboration with WHO

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International Atomic Energy Agency

CALIBRATION
OF REFERENCE DOSIMETERS
FOR EXTERNAL
BEAM RADIOTHERAPY

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CALIBRATION OF REFERENCE DOSIMETERS FOR EXTERNAL BEAM RADIOTHERAPY

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FOREWORD

Traceability, accuracy and consistency of radiation measurements are essential in radiation dosimetry, particularly in radiotherapy, where the outcome of treatments is highly dependent on the radiation dose delivered to patients. The role of Secondary Standards Dosimetry Laboratories (SSDLs) is crucial in providing traceable calibrations to hospitals, since they disseminate calibrations at specific radiation qualities appropriate to the use of radiation measuring instruments.

To contribute to harmonization and consistency in radiation measurements, the IAEA and the World Health Organization (WHO) created a network of SSDLs in 1976. To provide SSDLs with a practical guide on calibration and quality control procedures in radiotherapy dosimetry, the IAEA published a manual in 1995 entitled Calibration of Dosimeters Used in Radiotherapy (Technical Reports Series (TRS) No. 374). The manual was a revision of a report, Calibration of Dose Meters Used in Radiotherapy (TRS-185), published in 1979. Although much of TRS-374 remains relevant, there are a number of reasons for preparing a new report, including the development of new dosimetry standards and an increased emphasis on implementing quality assurance systems to help calibration laboratories provide documented assurance to the user community of their commitment to offering consistent and reliable results.

This report is not simply a revision of TRS-374, and should be regarded as a new publication with a new structure. Nevertheless, some material, especially that related to the calibration of dosimeters in terms of air kerma for kilovoltage X rays, has been extracted from TRS-374. It fulfils the need for a systematic and standardized approach to the calibration of reference dosimeters used in external beam radiotherapy by the SSDLs. It provides a framework for the operation of an SSDL within the international measurement system, a methodology for the calibration of instruments, and related quality control procedures to ensure traceability of radiation measurements in external beam radiotherapy.

This report is intended mainly for SSDLs, but the information is also useful for similar laboratories involved in the calibration of dosimeters used in external radiotherapy.

The IAEA express its thanks to its IAEA/WHO SSDL network co-secretariat and all authors and reviewers of this report. The editorial contribution of D. Burns is especially acknowledged.

The IAEA officer responsible for this report was A. Meghzifene of the Division of Human Health.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The IAEA, together with the World Health Organization (WHO), published a manual in 1995 [1] entitled Calibration of Dosimeters Used in Radiotherapy (Technical Reports Series (TRS) No. 374), which was a revision of a report published in 1979 [2].

1.2. OBJECTIVE

Although much of TRS-374 remains relevant, there are a number of reasons for preparing a new report. These include:

(a) Several Primary Standards Dosimetry Laboratories (PSDLs) provide calibration services in terms of absorbed dose to water for ^{60}Co gamma rays and a few provide a similar service for megavoltage X rays. New codes of practice based on absorbed dose calibrations, such as TRS-398 [3], describe how to use these calibration coefficients to determine the absorbed dose to water in various beams, and radiotherapy centres are adopting these codes of practice for their reference dosimetry. Secondary Standards Dosimetry Laboratories (SSDLs) are already facing an increase in requests for calibrations in terms of absorbed dose to water, and this report addresses this increased need for measurements in water.

(b) The international measurement system was strengthened by the introduction in 1999 of the Mutual Recognition Arrangement of the Comité international des poids et mesures (CIPM MRA) [4]. In particular, calibration and measurement capabilities (CMCs) have become an important focus for calibration laboratories and users.

(c) There is increased emphasis on implementing quality assurance systems to help calibration laboratories establish well defined and documented procedures and to provide documented assurance to the user community that the laboratory is committed to offering consistent and reliable results. The International Organization for Standardization (ISO), in cooperation with the International Electrotechnical Commission (IEC), has developed a standard (ISO/IEC 17025) [5] that can be used as the basis of a formal process for accrediting calibration laboratories. As an alternative to formal accreditation, the CIPM MRA proposes other options for demonstrating competence.

(d) There is increased emphasis on the reporting of uncertainties, and in 1995 the ISO published its Guide to the Expression of Uncertainty in Measurement [6], which provides guidance and recommendations on how to evaluate and report measurement uncertainties.

(e) In addition to providing details on the calibration of dosimeters for radiotherapy, TRS-374 contains considerable information on the calibration of instruments used for radiation protection. The IAEA has decided to issue a separate report on the calibration of these devices, which allows this report to focus on calibrations for radiotherapy.

(f) Some of the definitions and recommendations in TRS-374 are dated, incomplete or no longer needed. In a few cases, TRS-374 makes recommendations regarding certain parameters with little indication on how they might be determined.

1.3. SCOPE

This report is not a code of practice. It does not specify unique procedures for calibrating dosimeters. Instead, it recognizes that the services offered by PSDLs are evolving constantly to keep pace with advances in radiotherapy and equipment, and that there is a wide variety of users, from small to large organizations, with differing requirements. As a consequence, each SSDL must adapt its work to provide the best results under the different circumstances. Various calibration procedures are described, their relative advantages and disadvantages are discussed and criteria are put forward to help an SSDL decide which procedure is best suited to meet a particular requirement.

A typical SSDL will possess one or more X ray generators, with generating potentials in the range from 10 kV to 300 kV, as well as a ^{60}Co gamma ray unit. This report gives guidance on the setting-up, characterization and maintenance of such equipment. A modern radiation dosimeter used in radiotherapy consists of an air filled cavity ionization chamber connected by a coaxial cable to a measuring assembly (electrometer); there is sometimes an associated device for checking the long term stability of the instrument. In addition to a detailed discussion of the procedures to be adopted in calibrating these dosimeters, advice is given on the characterization, use, care and maintenance of the secondary standard reference dosimeter of the SSDL.

A major advance in radiotherapy over the past two decades is the widespread use of linear accelerators to produce high energy X ray and electron beams. Coupled with this has been the development of standards for absorbed dose to water and dosimetry based on ionization chamber calibrations in a water phantom. While accelerator facilities have not to date been employed in SSDLs, calibration in water forms an integral part of this report and indeed is the recommended method and the subject of TRS-398 [3].

A further significant development since the publication of TRS-374 has been the increased emphasis on the estimation of uncertainties and on quality assurance. These developments combine to give users of calibration services increased confidence in the reliability of calibration results. The preparation of an uncertainty budget and the implementation of a quality system are discussed in dedicated sections within this report.

1.4. STRUCTURE

Following this introduction, Section 2 describes the context within which SSDLs function. A new component is the establishment in 1999 of the CIPM MRA [4], which is an agreement among participating institutes, including the IAEA, to quantify the equivalence of their standards and to mutually recognize their calibration services. The CMCs of the laboratories that are signatories of the CIPM MRA are listed in the on-line key comparison database of the Bureau international des poids et mesures (BIPM) and constitute Appendix C of the CIPM MRA [7]. In principle, a customer can choose to have its dosimeter calibrated by any of these laboratories.

Section 3 defines and discusses the quantities kerma and absorbed dose, while Section 4 describes primary standards for air kerma and absorbed dose to water and gives typical values for uncertainties.

Section 5 describes the important characteristics of the calibration facilities needed by an SSDL. Most SSDLs operate kilovoltage X ray and ^{60}Co gamma ray facilities, and the key characteristics of these machines are described. The associated calibration equipment, including secondary standards and their characterization and the use of water phantoms for absorbed dose determination, is described in Section 6. Section 7 assumes the existence of facilities and equipment meeting the requirements laid out in Sections 5 and 6 and describes how to calibrate a dosimeter in terms of air kerma in a kilovoltage X ray beam or a ^{60}Co gamma ray beam, or in terms of absorbed dose to water in a ^{60}Co gamma ray beam.

Section 8 provides practical information to help an SSDL evaluate the uncertainty of its calibration coefficients. It draws on material from the ISO guide [6], as well as from a recent IAEA publication on this subject [8]. Finally, Section 9 describes the essential requirements for an SSDL quality system.

2. ROLE OF SECONDARY STANDARDS DOSIMETRY LABORATORIES

2.1. INTERNATIONAL MEASUREMENT SYSTEM

The international measurement system provides the framework for worldwide consistency in metrology by making available to the user community instrument calibrations that are traceable to primary measurement standards. These standards are themselves verified internationally through comparisons with similar standards operating around the world. A simplified representation of the international measurement system for radiation dosimetry is shown in Fig. 1.

A central laboratory in this framework is the BIPM. The BIPM, located in Sèvres (near Paris), is an international laboratory set up under the Metre Convention of 1875 to act in matters of world metrology, particularly concerning the demand for measurement standards [9] of increasing accuracy, range and diversity, and the need to demonstrate equivalence between primary standards. The BIPM is financed jointly by the Member States of the Metre

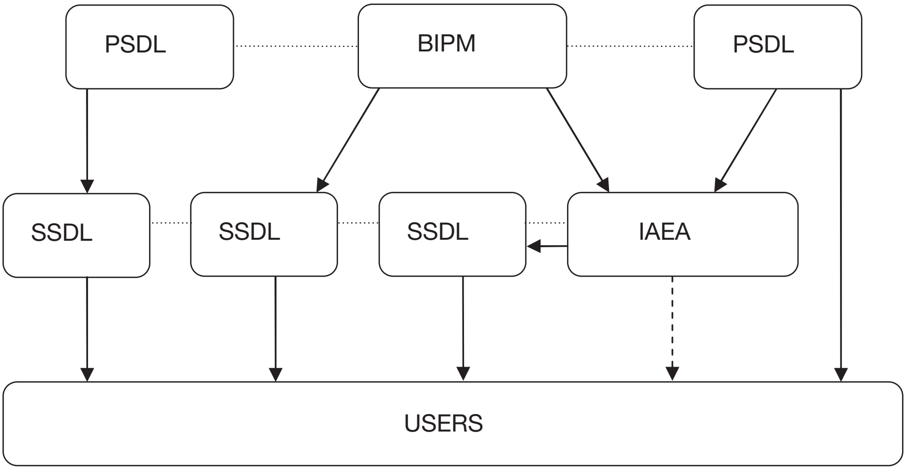

FIG. 1. A simplified representation of the international measurement system for radiation dosimetry. The dotted lines represent comparisons of primary and secondary standards and the arrows represent calibrations traceable to primary standards. It can be seen that an SSDL can obtain traceability either from the BIPM (if it is a national metrology institute (NMI) of the Metre Convention), a PSDL, or the IAEA. The dashed arrow represents exceptional calibration of a user instrument by the IAEA in the event that a country has no SSDL and limited resources.

Convention and operates under the supervision of the CIPM. Its mandate is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI) [10].

PSDLs that have developed primary standards for radiation measurements compare their standards with those of the BIPM in an ongoing series of bilateral comparisons. This permits the equivalence of any pair of primary standards to be assessed. The PSDLs then calibrate the standards of SSDLs, and these in turn calibrate user reference instruments. In parallel, the BIPM directly calibrates the secondary standards of national laboratories of the Metre Convention that do not hold primary standards. Importantly, the BIPM also calibrates the reference instruments of the IAEA, which itself calibrates the secondary standards of the IAEA/WHO network of SSDLs. In some instances users have direct access to calibration by a PSDL. Whatever the route, the international measurement system is structured to provide all users with access to instrument calibrations that are traceable to primary standards that have themselves been compared internationally.

2.2. COMITÉ INTERNATIONAL DES POIDS ET MESURES MUTUAL RECOGNITION ARRANGEMENT

A laboratory holding a recognized national standard for a given physical quantity, be it a primary or secondary standard, is referred to as a national metrology institute (NMI). In 1999, under the direction of the CIPM, NMI representatives of 38 Member States of the Metre Convention, Associates of the CGPM (the Conférence générale des poids et mesures) and two representatives of international organizations, including the IAEA, signed a mutual recognition arrangement (CIPM MRA) [4]. As of January 2008, the CIPM MRA has 89 signatories and covers a further 119 institutes designated by these signatories.

The CIPM MRA is the response to a growing need for an open, transparent and comprehensive scheme to give users reliable quantitative information on the degree of equivalence of national measurement standards and to provide for mutual recognition of the calibration and measurement services offered by participating institutes of the CIPM MRA. The process by which this is achieved involves a representative series of international comparisons of measurement standards referred to as key comparisons, supported by supplementary comparisons, quality systems and other demonstrations of competence by participating institutes, for example peer reviewed publications. The output from this process is a statement of the measurement capabilities of each participant in the key comparison database

(KCDB) maintained by the BIPM and publicly available on the BIPM web site [7]. This database includes a number of on-line appendices, notably Appendix B (Key and Supplementary Comparisons), which contains the results of key comparisons expressed in the form of key comparison reference values and degrees of equivalence of NMI standards, and Appendix C, which contains information on the CMCs declared by participating institutes.

In radiation dosimetry, the bilateral comparisons conducted by the BIPM on an ongoing basis over the past 40 years form a central part of the information contained in the KCDB. This information is complemented by multilateral comparisons organized by the Consultative Committee for Ionizing Radiation (Comité consultatif des rayonnements ionisants (CCRI)). However, the BIPM and CCRI comparisons by their nature are generally limited to a relatively small number of PSDLs. To extend participation worldwide, and to include the many NMIs that do not hold primary standards, a number of regional metrology organizations (RMOs) have been created. RMOs organize comparisons of national primary and secondary standards within their region. By including in these comparisons laboratories that have taken part in the corresponding BIPM or CCRI comparisons, the results of regional comparisons can be linked to BIPM and CCRI comparisons and hence to the KCDB.

The overall coordination of this structure is the responsibility of the BIPM under the authority of the CIPM. A joint committee of the RMOs and the BIPM, known as the JCRB, is responsible for analysing and transmitting entries into Appendix C of the CIPM MRA for the CMCs declared by the participating institutes. An important part of the approval process is the intraregional and interregional reviews of CMCs.

2.3. IAEA/WHO SECONDARY STANDARDS DOSIMETRY LABORATORY NETWORK

In 1976, the IAEA and the WHO strengthened implementation of the SI in radiation dosimetry by setting up a network of SSDLs to ensure the traceability of measurements, particularly for countries that are not members of the Metre Convention. As of January 2008, the SSDL network includes 76 laboratories and six SSDL national organizations in 64 IAEA Member States [11]. The SSDL network also includes 20 affiliated members, for example the BIPM, several PSDLs, the International Commission on Radiation Units and Measurements (ICRU), the International Organization for Medical Physics (IOMP) and several other international organizations.

2.3.1. Role of a secondary standards dosimetry laboratory

An SSDL is a laboratory that has been designated by competent national authorities to undertake the duties of providing the necessary link in the traceability of radiation dosimetry to national or international standards for users within that country. An SSDL is equipped with secondary standards traceable to either the IAEA, a PSDL or directly to the BIPM. The reference standards of about 50% of the SSDL network members are traceable to the IAEA, 30% to PSDLs and the remainder to the BIPM. SSDLs provide traceable instrument calibrations to users. The scope of the calibrations provided by SSDLs covers a wide range of services: external radiotherapy, brachytherapy, diagnostic radiology, including mammography, radiation protection and nuclear medicine. While some SSDLs offer the entire range of calibration services, others offer only one or two types of calibration.

The main function of an SSDL is to provide calibration services, including the dissemination of information on calibration procedures, and practical help to users of instruments in their particular application. Some SSDLs with the appropriate facilities and expertise can provide a range of additional services, such as:

(a) Postal dosimeters for dose comparisons for medical institutions within a country or region. This is done either by coordinating the distribution of thermoluminescent dosimeters (TLDs) from the IAEA/WHO postal service or the national/regional affiliated centres, or by providing the TLD service itself.
(b) On-site dosimetry audits with an ionization chamber and other appropriate equipment.
(c) Dose comparisons for radiation processing.
(d) Calibration services for personal radiation dosimeters.
(e) Postal dosimeters for patient dosimetry in diagnostic X rays.
(f) Maintenance of measuring instruments for users.
(g) Advice to users on quality assurance matters.
(h) National training courses in radiation measurement and calibration techniques, and in the use and maintenance of the instrumentation.

2.3.2. Metrological consistency of secondary standards dosimetry laboratories

To ensure that the calibration services provided by the SSDL network members to users follow internationally accepted standards, the IAEA has organized a comparison programme using ionization chambers to help the

SSDLs verify the integrity of their national standards and the procedures used for the transfer of the standards to users. The IAEA comparison programme with transfer ionization chambers includes the measurement of calibration coefficients for air kerma (N_K) and absorbed dose to water ($N_{D,w}$) in ^{60}Co gamma radiation. The results of the comparisons are confidential and are communicated only to the participants. This confidentiality is to encourage the participation of the laboratories and their full cooperation in the reconciliation of any discrepancy.

Prior to sending the selected ionization chamber to the IAEA, the SSDL is requested to make a check source measurement and to calibrate the chamber in terms of N_K and $N_{D,w}$. The calibrations at the SSDL and the IAEA are carried out under well defined reference conditions [12]. The ionization chamber is sent to the IAEA for calibration along with a data sheet that includes information from the SSDL on the chamber and its traceability, and the results of the check source measurements and those of the calibrations, including their uncertainties. After the chamber is calibrated at the IAEA, it is returned to the SSDL for repeat check source measurement and calibration. The SSDL reports the results of the repeat measurements to the IAEA. The results are analysed at the IAEA and transmitted only to the participant. Taking into account a previous analysis [1], which showed that a combined standard uncertainty of about 0.8% was achievable at the SSDLs for the calibration of dosimeters used in radiotherapy, the IAEA has set an acceptance limit of 1.5% for the results of these comparisons. The additional uncertainty arising from the calibration at the IAEA is not expected to increase the uncertainty of the comparison ratio significantly. SSDLs with results outside the acceptance limit are advised to review their calibration procedures, although they are not informed of the magnitude or sign of the discrepancy; following remedial action by the SSDL, an additional comparison is organized to demonstrate that the discrepancy has been resolved. Some SSDL members do not establish traceability to the BIPM, neither directly nor through the IAEA, and instead are traceable to a PSDL. The IAEA accounts for the known difference between the relevant standard at the PSDL and the corresponding standard of the IAEA. The results of the IAEA SSDL comparisons obtained during 2006 and 2007 are shown in Fig. 2.

2.3.3. Trends

The main role of the SSDLs will continue to be the provision of calibration services to users. The scope of the calibration services is expected to increase, especially in the field of diagnostic radiology. The IEC publication on the calibration of dosimeters in diagnostic radiology [13], and the recent IAEA

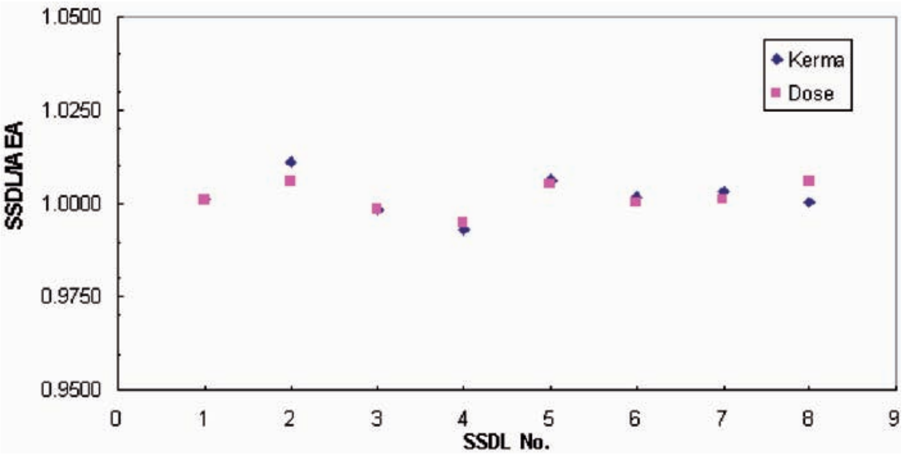

FIG. 2. Ratios of ionization chamber calibration coefficients between 2006 and 2007 supplied by the SSDLs to those measured by the IAEA. Diamonds correspond to calibrations in terms of air kerma and squares in terms of absorbed dose to water. Results are considered acceptable if the deviation from unity is less than 1.5%.

code of practice in this field [14], will probably lead to an increase in calibration requests by diagnostic radiology departments and also by radiation protection services for the assessment of patient doses. Brachytherapy, especially using high dose rate ^{192}Ir, is expanding in many countries. The implementation of quality assurance programmes for radioactivity measurements in nuclear medicine is also expected to lead to an increase in requests for calibrations in this area. Finally, there is a clear trend in many countries for the accreditation of calibration services in order to satisfy customer and regulatory requirements.

3. PHYSICAL QUANTITIES AND UNITS OF MEASUREMENT

There are two physical quantities used as a measure of the amount of radiation in external beam radiotherapy: kerma and absorbed dose. The definition of these two quantities can be found in ICRU Report 60 [15], and their detailed definition and realization are discussed in many textbooks on radiation dosimetry. The following discussion and that in Section 4, although not operationally essential, are included to facilitate a broader understanding of the primary standards and the physical quantities that they are designed to realize.

3.1. KERMA IN A MATERIAL

The kerma in a material is a quantity that is defined only for uncharged particles and is used in the present context for kilovoltage X ray and ^{60}Co gamma ray beams. When a small region R of a material m is irradiated by an external beam of photons, secondary charged particles are produced, mainly electrons. For ^{60}Co beams, these electrons are liberated mostly through Compton scattering interactions. For lower energy beams, photoelectric interactions become important, while at the higher energies produced by particle accelerators, pair production becomes significant. Very low energy electrons are also produced as the result of the relaxation of excited atoms or molecules (e.g. Auger electrons).

No matter the source of the charged particles, what is important is the total kinetic energy of all the charged particles liberated in the interactions of incident photons in the region R. The kerma in the material is the total kinetic energy of these liberated charged particles per mass of material m and is denoted K_{m}.

As a measure of kinetic energy per mass, the quantity kerma can be expressed in the SI system in the unit joule per kilogram, J/kg. However, the special name gray (Gy), was introduced for this purpose and should be used, noting the relation 1 Gy = 1 J/kg.

3.2. ABSORBED DOSE IN A MATERIAL

The charged particles resulting from the kerma proceed to interact with the material, primarily through ionization and excitation processes. The total energy absorbed within a small region R per mass of material m gives rise to the absorbed dose to the material, denoted by D_{m}.

In contrast to the kerma, the absorbed dose arises from energy deposition in R by any charged particles, not just those resulting from the interactions of incident photons in R. This includes contributions from charged particles that enter R from outside, as well as contributions from scattered Bremsstrahlung, annihilation and fluorescence photons produced within R. These considerations can be important for primary standards dosimetry, particularly when modelling radiation transport using Monte Carlo methods.

The inclusion in the absorbed dose of contributions from charged particles that enter *R* from outside means that the relationship between kerma and absorbed dose in *R* is well defined only when an equilibrium of charged particles exists, such that the total energy deposited in *R* by charged particles that enter from outside equals the total energy deposited outside *R* by charged particles liberated within *R*. This concept of charged particle equilibrium (CPE) and the extent to which it exists in a given measurement situation are important both in the determination of kerma using air ionization chambers (which respond to the absorbed dose to the air) and in the use of kerma to determine absorbed dose.

As for kerma, the unit of absorbed dose is the joule per kilogram (J/kg), with the special name gray (Gy). A word of caution is introduced here for the expression of the results of dosimetric measurements. It is not uncommon for confusion to arise between the physical quantity that is being determined and the unit of measurement that is used to express the amount of the quantity determined. Such confusion has led in some instances to the application of subscripts and other modifiers to the unit, for example the 'gray equivalent', $\mathrm{Gy}_{\mathrm{eq}}$. This practice, which is strictly forbidden within the SI, generally arises from a failure to state the quantity being determined.

Consider as an example the expression of the result of an air kerma determination as $K_\mathrm{a} = 1$ Gy. Here, the quantity is air kerma (K_a). The unit of measurement is the gray (Gy), and the amount is 1 Gy. Other quantities may also be expressed in terms of the gray, notably the absorbed dose to water. It is therefore a necessary requirement to state not only the measurement result (i.e. 1 Gy) but also the physical quantity determined (i.e. the air kerma).

3.3. KERMA AND ABSORBED DOSE FOR RADIOTHERAPY

In principle, both kerma and absorbed dose can be determined for any material at any energy. Given the considerations noted above regarding secondary photon contributions and CPE, it is not surprising that the relationship between kerma and absorbed dose changes significantly with energy and material.

In practical radiotherapy, it is the absorbed dose to the tissue of the patient that is of interest. As human tissue consists mainly of water, the quantity absorbed dose to water, D_w, has long been employed as a reference, and ultimately primary standards for absorbed dose to water are those that are required. However, because of the very limited beam penetration and the relatively low dose rates involved, absorbed dose is very difficult to measure directly for kilovoltage X rays [16], and existing standards for these radiations are almost all based on kerma, in particular on the determination of the air kerma using a free air ionization chamber. A dosimetry code of practice or protocol, for example TRS-277 [17], is then used to determine the absorbed dose to water under reference conditions using a cavity ionization chamber having an air kerma calibration coefficient.

For ^{60}Co energies, the need for CPE would require a prohibitively large free air chamber, and hence cavity ionization chambers are used as primary standards, with the consequent need to introduce cavity theory. In more recent years, the direct determination of absorbed dose by graphite and water calorimetry has produced standards with an overall uncertainty that matches, and in some cases surpasses, that derived from a determination of air kerma. Nevertheless, air kerma for ^{60}Co remains a very important reference quantity, particularly for standards laboratories.

At the high energies produced by particle accelerators, the determination of air kerma free in air in these beams is no longer a useful means to determine absorbed dose. Traditionally, dosimetry protocols, for example TRS-277 [17], have been used to determine absorbed dose using an ionization chamber with a ^{60}Co air kerma calibration. In more recent years, absorbed dose standards operating at high energies have been used, either directly for instrument calibrations or more commonly to determine values for correction factors that convert an ionization chamber ^{60}Co absorbed dose calibration for use at higher energies [3].

4. PRIMARY STANDARDS AND THEIR DISSEMINATION

A primary standard for a given physical quantity is an instrument of the highest metrological quality that permits determination of a unit of the quantity without reference to other standards of the same quantity. Although SSDLs do not normally operate primary standards, they do rely on secondary standard instruments that have been calibrated against primary standards. Operationally, SSDLs can use their calibrated secondary standards without knowledge of how the primary standards are established. However, some knowledge of the primary standards can be helpful in understanding the calibration certificate provided by the PSDL. The intent of this section is to give a brief review of the operating principles and uncertainties of primary standards for air kerma and absorbed dose to water and to describe how the secondary standards of the SSDLs are calibrated against these primary standards.

4.1. PRIMARY STANDARDS FOR AIR KERMA

4.1.1. Kilovoltage X rays

As noted in Section 3.3, although the quantity of interest is D_w, the realization of this quantity in kilovoltage X rays is best achieved through the measurement of $\dot{K}_a$ using a free air ionization chamber. In this device, an entrance diaphragm with an aperture of known area and a collecting plate of known length (in the beam direction) are used to define a photon interaction volume of air within a larger air volume. If the dimensions of the larger air volume are such that no secondary electrons generated within the interaction volume can reach the chamber walls, the chamber can be considered 'wall-less'. Under these conditions, the air kerma rate at the reference plane of the diaphragm is determined using:

$$\dot{K}_a = \frac{I}{m_a} \frac{(W_a/e)}{(1-g)} \prod_i k_i \qquad (1)$$

where

I is the ionization current;
m_a is the mass of air in the measurement volume;
W_a is the mean energy required to create an ion pair in dry air;
e is the charge of the electron;
g is the correction for radiative losses.

Several correction factors k_i are required, the most important being k_a and k_{sc}, the corrections for photon attenuation and scattering, respectively, in the air path from the reference plane of the entrance diaphragm to the centre of the measurement volume, k_e, the correction for electron losses to the chamber walls, and k_{fl}, the correction for fluorescence generated in the argon of the air.

The combined standard uncertainty in the determination of air kerma using a free air chamber is typically 0.2–0.3%. A dominant component is the uncertainty for W_a. The value $(W_a/e) = 33.97$ J/C recommended by the CCRI in 1985 [18] has a stated standard uncertainty of 0.15%. Significant uncertainties also arise from the correction factors k_{sc}, k_{fl} and in some cases k_e, although knowledge of these factors has improved in recent years through the use of Monte Carlo simulations [19–22].

International comparisons of free air chambers are conducted on an ongoing bilateral basis. For low energy X rays (up to 50 kV generating potential), the free air chambers are generally transportable and comparisons are carried out directly at the BIPM. For medium energies (100–300 kV), most laboratories have a separate standard that is significantly larger and not transportable. These are compared indirectly using cavity ionization chambers as transfer devices, calibrated at the PSDL and at the BIPM. The results of these international comparisons are available on-line in the KCDB of the BIPM [7].

The calibration of secondary standard ionization chambers against free air chambers is normally performed free in air, by substitution, at reference distances of 0.5–1.5 m from the X ray source in a circular radiation field of diameter of the order of 10 cm. The subsequent use of a calibrated secondary standard at an SSDL is discussed in Section 7.

4.1.2. Cobalt-60 gamma rays

As noted in Section 3.3, despite the development of absorbed dose standards for ^{60}Co, air kerma standards still have an important role to play in reference dosimetry. Free air chambers are not feasible at these energies and the standards are cavity ionization chambers of various sizes and shapes. The choice of wall material is invariably graphite because of its similarity to air (and to water) in terms of radiation interaction coefficients.

The realization of air kerma using an air filled cavity ionization chamber is more complex than that using a free air chamber. The measured ionization current I per mass m_a relates closely to the mean absorbed dose rate to the air of the cavity. The electrons giving rise to this absorbed dose rate are generated in the graphite wall, which gives rise to a ratio of mean mass stopping powers, $s_\mathrm{c,a}$. The generation of these electrons by photon interactions in graphite rather than in air gives rise to a ratio of mean mass energy absorption coefficients $(\mu_\mathrm{en}/\rho)_\mathrm{a,c}$. The expression for the air kerma rate is then:

$$\dot{K}_\mathrm{a} = \frac{I}{m_\mathrm{a}} \frac{W_\mathrm{a}}{e} \frac{(\mu_\mathrm{en}/\rho)_\mathrm{a,c}}{(1-g)} s_\mathrm{c,a} \prod_i k_i \qquad (2)$$

Among the correction factors k_i are the factor k_wall that corrects for attenuation and scattering of photons in the chamber wall and the axial non-uniformity factor k_an (sometimes replaced by the point source non-uniformity factor k_pn) that corrects for the sensitivity of the chamber response to the divergence of the beam.

The standard uncertainty in the determination of air kerma using a cavity standard is in the range from 0.2% to 0.3%. Determination of the air mass m_a requires knowledge of the cavity volume, a measurement that can introduce a standard uncertainty in excess of 0.1%. Most standards are either spherical or cylindrical in design, and a significant uncertainty component can arise from k_{wall}. In contrast, for a parallel plate design (employed, for example, at the BIPM) the value for k_{wall} is small, although in this case the value for k_{an} is larger [23]. The values for k_{wall} and k_{an} and their uncertainties have been revised in recent years for many standards as a result of better information made available through Monte Carlo calculations [24–28].

It is of note that the 0.15% uncertainty for W_a noted in the preceding section does not enter directly here. This is because the product $W_a s_{c,a}$ is determined in part from experiments in which graphite walled ionization chambers of known volume are compared with graphite calorimeters, resulting in the uncertainty for the product $W_a s_{c,a}$ of 0.11% recommended by the CCRI [29]. The uncertainty for $(\mu_{en}/\rho)_{a,c}$ is generally taken to be around 0.05%.

As for X rays, international comparisons of ^{60}Co air kerma standards are conducted on an ongoing bilateral basis. Since the chambers are transportable, comparisons are normally carried out directly at the BIPM. The results of these international comparisons are also available on-line in the BIPM KCDB [7].

The calibration of reference ionization chambers against ^{60}Co cavity standards is normally performed free in air at a reference distance of 1 m from the source, in a square radiation field of side 10 cm. Typically, the reference instrument is not calibrated directly against a primary standard, but rather the air kerma rate at the reference point is known from long term measurements made using the primary standard. The subsequent use of the calibrated chamber at an SSDL is discussed in Section 7.

4.2. PRIMARY STANDARDS FOR ABSORBED DOSE TO WATER

The primary standards for absorbed dose to water for ^{60}Co gamma rays and for higher energy photons are essentially the same. Three techniques have been used.

The first is based on ionization chamber dosimetry and has much in common with the cavity standards used to determine air kerma, as described in Section 4.1. The BIPM standard for absorbed dose to water is based on this approach [30]. The cavity standard (with a waterproof envelope) is positioned at a reference depth in a water phantom. The measurement equation for the absorbed dose rate to water is:

$$\dot{D}_{\mathrm{w}} = \frac{I}{m_{\mathrm{a}}} \frac{W_{\mathrm{a}}}{e} \Psi_{\mathrm{w,c}} \left(\mu_{\mathrm{en}}/\rho\right)_{\mathrm{w,c}} \beta_{\mathrm{w,c}} s_{\mathrm{c,a}} \prod_i k_i \tag{3}$$

where

$\Psi_{\mathrm{w,c}}$ is the ratio of photon fluences in water and graphite;
$\beta_{\mathrm{w,c}}$ is the ratio of absorbed dose to collision kerma ratios.

The other symbols have the same meaning as in Eq. (2). Among the correction factors k_{i}, the most significant is k_{cav} for the presence of the air cavity. As for cavity standards for air kerma, one limitation of this method is that the recommended value for W_{a} is derived in part from measurements involving graphite calorimeters and the method is therefore not independent of D_{w} standards based on graphite calorimetry (see below).

A second approach is to use a chemical dosimeter, such as the Fricke dosimeter. In this dosimeter, irradiation of the Fricke solution leads to the production of ferric ions, which have a well defined absorption spectrum. The absorbance, or optical density (OD), is proportional to the energy absorbed from the radiation field and thus the absorbed dose to water can be obtained using:

$$D_w = \frac{\mathrm{OD}}{L\rho_{\mathrm{F}}\varepsilon G} \tag{4}$$

where

L is the optical path length of the solution;
ρ_{F} is the density of the Fricke solution;
ε is the extinction coefficient of the ferric ion;
G is the chemical yield of the ferric ion.

To use this technique as a primary standard, G must be measured without reference to any other determination of the quantity D_{w}. This has been done at some PSDLs using a total absorption technique in which an electron beam with well known energy is completely absorbed in the Fricke solution [31, 32].

The third and most widely used technique for establishing the absorbed dose to water is based on calorimetry. In this approach, use is made of the fact that in many materials most of the energy absorbed from the radiation field appears as heat. If the conversion to heat is complete, the absorbed dose to material m is given by:

$$D_m = c_m \Delta T \tag{5}$$

where

c_m is the specific heat capacity of the material;
ΔT is the measured temperature rise.

The specific heat capacity can be measured without reference to a standard of absorbed dose and ΔT can be made traceable to the SI unit of temperature. The main challenge in calorimetry is to determine the fraction of the energy absorbed from the radiation field that does not appear as heat, referred to as the heat defect. There are various processes that might contribute to a heat defect, but the most likely is radiation induced chemical reactions.

Although in principle an absorbed dose calorimeter can be made from any material, the most widely used for establishing the absorbed dose to water are graphite and water. Graphite is used in many PSDLs [33–38] because its radiation interaction characteristics are similar to water and, being a solid, it permits the construction of well defined absorbing elements such that the core, in which the temperature is to be determined, can be thermally isolated from its surroundings. Measurement and theory also indicate that any heat defect in graphite should be small. The main disadvantage of graphite calorimetry is that a conversion process is necessary to obtain the absorbed dose to water.

Several PSDLs have adopted water calorimetry as their standard for absorbed dose to water [39–43]. The principle advantage of water as the calorimetric medium is that it gives the absorbed dose to water in a direct manner. The main technical challenges are to construct a temperature probe and water containment vessel that have a minimal effect on the temperature measurement, to quantify the residual effect and to establish the heat defect because, as a liquid system, radiation induced chemical reactions can lead to a significant heat defect. Despite their differences, the uncertainty of the absorbed dose to water determination is similar for both graphite and water calorimetry.

Calorimetric techniques for establishing primary standards for absorbed dose to water are technically demanding and time consuming and consequently secondary standards are not calibrated directly against the primary standard. Instead, the PSDL uses the primary standard to calibrate its own working standards. Typically, these are high quality ionization chambers with a precision at least as good as that of a secondary standard.

4.2.1. Cobalt-60 gamma rays

Calibration services based on primary standards for absorbed dose to water are well established for ^{60}Co gamma rays and are offered by a number of PSDLs. In addition, the BIPM uses its ionometric absorbed dose standard to calibrate the secondary standards of many national laboratories, as well as those of the IAEA. Details of the calibration services offered by laboratories can be obtained by consulting the on-line CMCs in Appendix C [7] of the CIPM MRA.

Calibrations are carried out by positioning the ionization chamber (or other suitable detector) at the reference point in a water phantom. This means that the ionization chamber must either be intrinsically waterproof or enclosed in a suitable protective sleeve. Typically, a PMMA sleeve with a wall thickness of about 1 mm is used.

Since the ^{60}Co units used at PSDLs are well characterized, a PSDL will not generally use a primary or working standard for each calibration. Instead, the absorbed dose rate at some reference time is calculated from the value established using the primary standard, taking into account the estimated source decay.

Although the standard uncertainty of calibration coefficients differs slightly between laboratories, it is typically about 0.5%, with most of the uncertainty arising from the primary standard and not from the performance of the dosimeter being calibrated. The calibration coefficient of a good dosimeter (typically consisting of an ionization chamber and electrometer) can be expected to be stable to better than 0.5% over many years.

4.2.2. Megavoltage X rays and electrons

The National Physical Laboratory in the United Kingdom was the first PSDL to offer a calibration service for megavoltage X rays [44], but now a number of PSDLs offer a similar service. These laboratories are listed in the on-line CMCs [7] of Appendix C of the CIPM MRA.

Owing to the variability of the output of the accelerators used to generate high energy X rays, the PSDL must use working standards to calibrate secondary standard dosimeters. Two modes of dissemination are in operation: a direct calibration of individual secondary standards in accelerator beams or the use of a correction factor, k_Q, applied to the calibration coefficient determined in a ^{60}Co beam. These k_Q factors are given as a function of X ray beam quality and ionization chamber type in an associated code of practice, notably the IAEA Code of Practice in TRS-398 [3].

For those clinics offering therapy using high energy X ray beams, a direct calibration offers several advantages. No code of practice is needed to derive the required calibration coefficient from a ^{60}Co calibration coefficient and the uncertainty of the calibration coefficient is smaller because no k_Q factor is required. Since each chamber is calibrated in a high energy beam, no assumption is made that all ionization chambers of the same type have the same energy response.

Calibration services for high energy electron beams are less widely available than those for megavoltage X rays. A list of the relevant calibration services can be obtained from the on-line CMCs [7] in appendix C of the CIPM MRA. The uncertainties for k_Q factors given in the relevant codes of practice are larger for electron beams than for X rays, and there is considerable evidence that the wall correction factors for parallel plate ionization chambers are larger than previously estimated [45]. The wider availability in the future of primary standards for electron beams can be expected to improve dosimetry in this area.

Only a few PSDLs and no SSDLs have their own accelerators for the purpose of calibrating dosimeters in terms of absorbed dose to water. PSDLs and SSDLs that are not equipped with accelerators cannot realize or transfer standards for absorbed dose to water for megavoltage X rays and high energy electrons to users in radiotherapy centres. Consequently, all of the hospitals in countries where such calibrations are not available must use a dosimeter with a ^{60}Co calibration coefficient in terms of absorbed dose to water along with k_Q factors given in TRS-398 [3]. A potential solution to this limitation, aside from SSDLs acquiring accelerators, is for an SSDL to hold a secondary standard that is calibrated in an existing accelerator and to take this standard to radiotherapy centres for cross-calibration of the local reference instrument in an accelerator beam. The overall uncertainty achievable by an SSDL for such a cross-calibration in a non-laboratory environment should be assessed and compared with the corresponding uncertainty using the k_Q factors of TRS-398.

4.2.3. Kilovoltage X rays

Calorimetry becomes technically challenging for kilovoltage X ray beams because of the steep dose gradients and low dose rates. The Physikalisch-Technische Bundesanstalt in Germany has used an extrapolation ionization chamber and the technique summarized by Eq. (3) to develop an absorbed dose standard for kilovoltage X rays [16]. A list of calibration services for kilovoltage X rays can be obtained from the on-line CMCs [7] of Appendix C of the CIPM MRA.

5. CALIBRATION FACILITIES

This section gives guidance and recommendations on setting up X ray and gamma ray calibration laboratories and characterizing the radiation beams. Many factors can affect the quality of the calibrations performed by an SSDL. Two important elements are the characteristics of the laboratory space and the stability of the environmental conditions. While it is difficult to give detailed recommendations regarding laboratory space, such as the size of the rooms, the following general remarks are made:

(a) The radiation laboratory in which calibrations are made should be separated from areas in which there are other activities. Access to and the use of areas related to calibrations should be controlled.
(b) Enough storage space should be provided in the room where calibrations are made to house connectors, adapters, tools and accessories so that these items are easily available when needed.
(c) Reference standard instruments and other items of calibration equipment, including user dosimeters, should be carefully protected and stored in a location where the risk of damage or loss is minimized.
(d) The rooms where calibrations are performed, or where reference standard instrument calibration equipment and user dosimeters are stored, should be air conditioned to minimize variations of temperature and humidity of the ambient air. The environmental conditions (temperature, pressure, humidity) in the radiation laboratory should be monitored and recorded. Calibrations should be stopped when the environmental conditions could jeopardize the results of the calibration. The SSDL should define and document limits for the environmental conditions within which calibrations will be performed (see, for example, Ref. [46] for guidance).
(e) Measures should be taken to ensure good housekeeping in the laboratory. Staff engaged in cleaning the laboratory should be supervised or trained to ensure that cleaning operations are carried out safely and without risk of influencing the quality of calibrations.

5.1. X RAY CALIBRATION LABORATORY

A schematic diagram of a suitable layout of the apparatus for calibrating dosimeters in X rays is shown in Fig. 3. The elements that need to be carefully aligned with the beam axis during the calibration procedure should be mounted on a bench with suitable holders and alignment stages for precise adjustment. All components should be rigidly mounted and positioned so as to minimize scattered radiation at the position of the ionization chambers. To this end, it is good practice to place the diaphragms, shutter, filters and monitor chamber as close to the X ray tube as possible. The optical bench arrangement used at the IAEA Dosimetry Laboratory is shown in Fig. 4.

5.1.1. X ray generators

The term ‘X ray generator’ is used here to refer to the combination of a high voltage generator and X ray tube. Usually a single X ray generator cannot provide X ray qualities over the entire range from about 10 kV to 450 kV used in radiotherapy. Consequently, unless calibrations are to be performed over a limited range, more than one X ray generator is required.

A low inherent filtration is required for an X ray tube to be used effectively down to the lowest generating potential. The inherent filtration of a tube used for the lower energy range (about 10–60 kV), plus the filtration of any monitor ionization chamber, should not be more than around 3 mm of beryllium equivalent; for the higher energy range it should not be more than

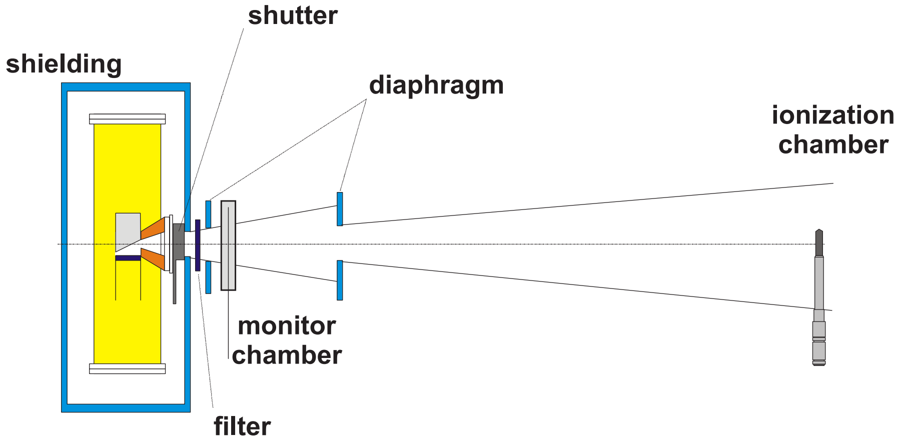

FIG. 3. Calibration arrangement for X ray beams, showing the preferred arrangement of shutter, filter, diaphragm and monitor chamber.

FIG. 4. Measuring bench at the IAEA Dosimetry Laboratory showing a holder for three ionization chambers, mounted on a translation stage, for measurements in air (centre), a water phantom on an elevated rigid frame (left) and a fine focus alignment device (right). The measuring bench can be moved in the beam direction along supporting rails.

about 4 mm aluminium equivalent (for the measurement of the inherent filtration see, for example, Section 4.2.3.2 of Ref. [47]). The inherent filtration changes by a small amount as a tube ages, an effect that might be significant at the lowest energies. This will be determined during the periodic half-value layer (HVL) measurements (see Section 5.2.3). To simplify the measurement of beam profiles, the tube should be fixed with the electron beam axis either horizontal or vertical.

It should be possible to display the value of the generating potential to within 1%. Ripple of the generating potential is a consideration and X ray generators are commercially available that have a ripple (measured under load) of less than 1%.

Regarding the electrical safety of installations, all local and national regulations concerning electrical equipment must be observed. Installation must be carried out by qualified personnel and the instructions supplied by the manufacturer must be followed. After installation, a check must be made that all accessible parts of the X ray generator and the calibration bench are properly grounded.

Particular attention should be given to the high voltage cables. These should be firmly clamped so that no undue movement can take place, but they must also be capable of moving freely whenever the X ray tube needs to be moved. Care should be taken that the cables are not rubbed repeatedly, as this might damage the outer insulation. Cables should never be pulled, or bent into an arc of small radius. They should be inspected frequently to confirm that they are free from visible damage.

5.1.2. Diaphragms and shutter

There are typically two or three diaphragms in an X ray calibration facility. An initial diaphragm is often supplied as part of the tube housing. It serves to limit the field size to the largest field expected to be used and should be as close as possible to the tube.

A second, beam limiting diaphragm defines the size of the beam at the point of measurement. To permit measurements with different field sizes, it should be either adjustable or interchangeable. Its thickness should be sufficient to transmit less than 0.1% of the radiation incident on the diaphragm.

A third, shielding diaphragm is optional and can be used to reduce the effect on the monitor chamber of radiation backscattered from any chamber positioned at the point of measurement. Its aperture should be chosen to reduce penumbra but should not limit the beam.

A suitable shutter system must either be purchased or constructed. The shutter serves two purposes. Firstly, it attenuates the radiation to a safe level for personnel. This provides improved X ray beam stability by making it unnecessary to switch off the generating potential when personnel need to access the radiation area. Secondly, it begins and terminates each irradiation. A common arrangement is to have a sliding block of shielding material combining the functions of the shutter and the initial diaphragm. Timing uncertainties related to shutter movement are discussed in Section 5.2.4.

5.1.3. Radiation qualities and filters

Different X ray qualities are produced by changing the generating potential and the beam filtration. The radiation qualities offered by the SSDL for calibration of dosimeters should be suited to the particular needs of radiation therapy in that part of the world. The SSDL should offer a range of qualities such that each dosimeter can be calibrated at X ray qualities lower in energy than, and at least as high in energy as, any that are to be measured by that dosimeter, as well as at several qualities between these limits. In addition, the SSDL should try to reproduce the qualities used to calibrate the secondary standard at the PSDL or the BIPM. Additional X ray qualities that can be used for the calibration of dosimeters are described in Ref. [47]. For calibrations, the tube current should be set such that the air kerma or absorbed dose rate is in the range from around 10 mGy/min to 1 Gy/min.

As an example, the low and medium energy X ray qualities used at the BIPM to calibrate dosimeters for radiotherapy are given in Table 1.

Filters should be made from metal with the highest purity readily available (see Table 9 in Ref. [47]). Particular attention should be paid to avoiding impurities of higher atomic numbers. They should be as homogeneous as possible, without visible flaws (pinholes, cracks, macroscopic grains). Filters should be mounted as close as possible to the shutter, and the individual elements should be arranged, from the focus, in decreasing order of atomic number (to reduce fluorescent radiation from elements with higher atomic number). Suitable sets of filter combinations can be mounted on a wheel to facilitate changing radiation qualities.

5.1.4. Monitor chamber

For calibrations in X rays, unless the tip to tip method is used (Section 7.1.1), a monitor chamber is normally required. The monitor is typically a parallel plate transmission ionization chamber positioned to accept the entire collimated beam after it has passed through the beam limiting diaphragm and the filters. As far as possible, the radiation field should not be

TABLE 1. X RAY QUALITIES USED FOR DOSIMETER CALIBRATIONS AT THE BIPM

Generating potential (kV)	Half-value layer	
	Aluminium (mm)	Copper (mm)
10	0.037	—
30	0.17	—
25	0.24	—
50[b]	1.0	—
50[a]	2.3	—
100	4.0	0.15
135	—	0.50
180	—	1.0
250	—	2.5

[a] Commonly referred to as the 50 kVa quality.

[b] Commonly referred to as the 50 kVb quality.

disturbed by the monitor chamber. The thin chamber windows are considered as part of the inherent filtration of the X ray beam (Section 5.1.1).

Dosimeter readings are normalized to the corresponding monitor chamber reading. For each radiation quality, the monitor chamber reading relative to the secondary standard, or to any working standard, at a given position should be constant in time. This information will be accumulated during routine calibration activities and can be used as part of the stability check system (Section 6.1.7). A significant deviation from the expected value indicates a change in the monitor, the secondary or working standard, or the radiation quality and must be investigated immediately.

The monitor chamber is also of use during the commissioning of an X ray facility for the measurement of field uniformity (Section 5.2.2) and of HVL (Section 5.2.3).

5.1.5. Ionization chamber support and positioning

The support system for ionization chambers should be capable of adjustment, particularly in the axial direction, and of holding chambers rigidly. When possible, the support should be wholly outside the radiation field in order to minimize scattered radiation at the measurement position. For certain chamber types, for example those with no rigid stem, this might not be possible. In this case those elements of the support that are in the beam should be as small as practicable and of a light material, for example PMMA. The interchange of the reference ionization chamber and the ionization chamber to be calibrated should be possible using mechanical devices with simple and precise operation. If absorbed dose to water is to be determined, the table must be capable of supporting a water phantom.

To facilitate chamber positioning on the horizontal and vertical axes perpendicular to the beam, it must be possible to represent, either mechanically or optically, the central axis of the beam. A laser or light beam can provide an easy alignment system. For accurate positioning of distance from the source, an easily removable and replaceable device should be available to check the axial position of chambers. Alternatively, a telescope or other optical device mounted perpendicular to, and outside of, the beam of radiation can be used.

5.2. CHARACTERIZATION OF X RAY FACILITY AND BEAMS

Every effort should be made to ensure that the X ray facility is correctly adjusted by the manufacturer at the time of installation. Certain tests, however, must be carried out by the SSDL staff before the equipment is used for the calibration of dosimeters, and should be repeated periodically to ensure that the equipment remains in good working order.

The quantitative criteria for instrument performance given here are generally accepted values in the field of radiation dosimetry. In the event that the equipment available does not fulfil these criteria, this should be accounted for in the uncertainty budget for the calibration.

5.2.1. Leakage and stray radiation

The leakage radiation escaping the shielding of an X ray tube must be as low as reasonably achievable, not only for the safety of personnel but also to ensure that the radiation level will not interfere with equipment or signal cables in the measurement room. The existence and position of any weak points in the shielding can be determined by using a suitable radiation survey meter. The main beam should be blocked by closing the shutter. For these tests, the tube should be operated at its maximum operating potential and current.

A radiation survey must also be made of the stray radiation level (i.e. the radiation level measured around the external perimeter of the room containing the X ray tube when the shutter is open).

The leakage and stray radiation levels should not exceed the limits specified by local or national regulations.

5.2.2. Determination of beam centre and field size

The beam axis is defined by the focal spot of the X ray tube and the centre of the beam limiting diaphragm. In practice, the position of the focus is not accurately known and in the first instance the beam axis is assumed to pass through the centres of the initial and beam limiting diaphragms.

To accurately determine the location of the beam axis at the calibration distance, a measurement should be made of the relative response of a small volume ionization chamber on the horizontal and vertical axes perpendicular to the beam axis (see Fig. 6 for an example of a data set for a ^{60}Co facility). From these data, the field size on each axis is determined as the distance between the two 50% points. The beam centre is defined by that point lying midway between the four 50% points, although several horizontal and vertical iterations might be required to locate this point.

These data also give a measure of the beam uniformity and can be used to estimate the uncertainty arising from beam non-uniformity, or to derive appropriate correction factors if necessary. The beam uniformity might depend on the tube voltage and should be measured at least at the extremes of operating voltage. Owing to the heel effect, the beam uniformity will be different in the horizontal and vertical axes, and, on that axis parallel to the electron beam axis of the tube, will not be symmetric about the beam centre.

5.2.3. Measurement of the half-value layer

The HVL (i.e. the thickness of aluminium or copper required to reduce by half the air kerma rate at the calibration distance) should be determined using an ionization chamber for which the variation in the air kerma calibration coefficient as a function of HVL is known to be small. Given this condition, the response of the ionization chamber when different absorbers are placed in the beam can be taken to represent the relative air kerma rate.

For X ray qualities of 100 kV and above, absorbers of copper are used; copper sheets of known thickness between 0.1 mm and 5 mm are generally required. For qualities below 100 kV, aluminium is better suited (copper filters would be too thin and fragile) and aluminium sheets of thickness between 0.02 mm and 5 mm are required. The metals should have a purity of at least 99.9% (see table 9 in Ref. [47]). The absorbers should have adequately uniform thickness and should be as homogeneous as possible (without visible pinholes, cracks, macroscopic grains).

The absorbers should be positioned midway between the monitor chamber and the measuring chamber so as to minimize radiation scattering into either. The field size should be the smallest available that irradiates the sensitive volume of the chamber completely and reasonably uniformly. Each absorber must be substantially larger than the X ray beam so that it intercepts the beam completely.

All readings of the ionization chamber should be normalized to the monitor chamber. Initially, the normalized chamber reading should be determined in the absence of absorbers, and this measurement should be repeated at intervals and as the last measurement in the HVL determination. The normalized readings should be determined for several values of absorber thickness that give readings in the neighbourhood of 50% of the initial reading, and also in the neighbourhood of 25% if the second HVL is to be determined. The attenuation curve $\ln\{I\}$ versus absorber thickness should be plotted, where I is the normalized chamber reading. The HVL is derived by interpolation from this graph, as shown in Fig. 5.

For a given generating potential and filter combination, the measured HVL should agree with the expected value within about 2%, which is a typical uncertainty for a measurement of HVL (a larger deviation is acceptable below 20 kV). If this is not the case, the thickness and density of the filters and the

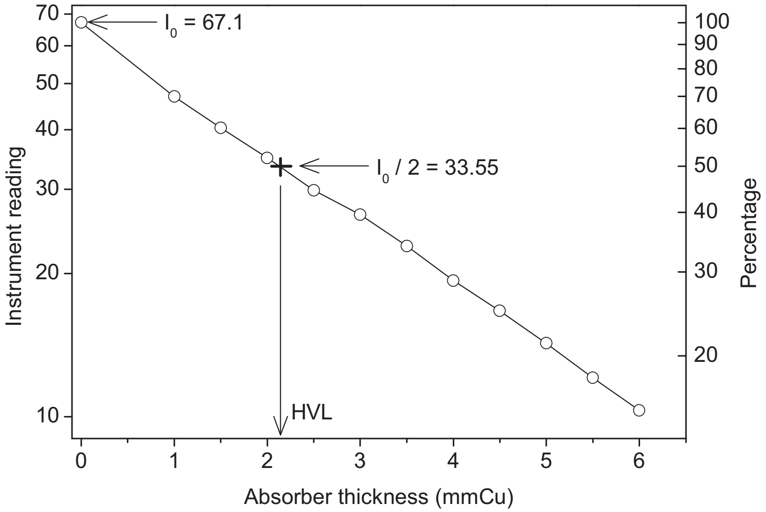

FIG. 5. Determination of the HVL by interpolation. The chamber reading I is measured for different values of absorber thickness and a plot made of ln{I} as a function of absorber thickness. The first HVL is the absorber thickness corresponding to a reading of 50% of the reading I_0 with no absorber.

absorbers used to measure the HVL should be verified. If these are correct, the filtration should be adjusted to obtain the desired HVL (within 2%). The generating potential should not be adjusted for this purpose unless there is independent evidence that the generator voltage calibration is in error. Additional guidance on HVL measurements can be found in Ref. [13].

Although the procedure described above is adequate for most purposes, the SSDL can improve the accuracy of HVL measurements by accounting for the effect of the field size. The measured HVL depends to some extent on the field size, mainly because of scatter in the absorbers positioned between the monitor and chamber. By carrying out the measurements for three or more field sizes, it is possible to extrapolate to zero field size, and thus to obtain the correct, small field HVL.

It should be noted that the HVL might change slightly over time due to a change of the inherent filtration of the X ray tube with age and usage. This is particularly true for the lowest HVLs and it is therefore advisable to remeasure these from time to time, particularly if the tube output for a given generating potential and tube current appears to have decreased. Additional information on measuring HVL can be found in Refs [48, 49].

5.2.4. Timing uncertainties

The measurement time is of no importance when calibration is performed tip to tip, or by substitution using a monitor (see Section 7.1.1), and needs to be known only when calibration by substitution is performed without a monitor. In this case, in which the tube current needs to be well controlled, the parameter of importance is the ratio of the measurement times. Timing uncertainties can arise from different causes depending on the details of the calibration procedure.

Most electrometers have an internal time base by which the measurements can be started and stopped, using a pre-set time, with the beam continuously on. The recommended method of working is to use the internal timer of the electrometer, or alternatively an external electronic timer linked to the electrometer, with the beam shutter open all the time. This method avoids uncertainties due to a variation of the output rate at the beginning and end of the irradiation due to the motion of the shutter, and also avoids the use of the built-in timer of the X ray facility, which might be influenced by short term instabilities in the mains frequency (a significant problem in some countries). Measurement with the shutter open throughout also avoids the possibility that in tip to tip calibration one chamber might be irradiated for an appreciably longer time than the other. The time base of the electrometer, or any external electronic timer used, should be checked regularly against a time signal or an accurate clock.

If the dosimeter does not have an electronic timer, for example dosimetry using TLDs, the irradiation time should be determined by measuring the time between the opening and closing of the shutter. Beginning and ending an irradiation by switching the X ray generating potential on and off should be avoided, as it leads to appreciable uncertainty in the irradiation time, instabilities in the beam and might considerably shorten the life of the X ray tube.

On opening the shutter, the output rate rises from zero to its steady state value over a finite period of time. Similarly, on closing the shutter, the output rate does not fall to zero instantaneously. The uncertainty of the irradiation time can be as large as 100 ms. To minimize this uncertainty, the time measurement should be synchronized with the shutter motion. The most representative timing will generally be achieved if the irradiation is timed from the midpoint of the rise in output rate to the midpoint of the fall. This can be accomplished by adjusting the timing mechanism so that the timer is started and stopped as the edge of the shutter crosses the axis of the beam.

There are two components of uncertainty relating to timing. To estimate the random uncertainty, a series of at least ten output measurements should be made using an ionization chamber at the calibration position, each irradiation having the same nominal duration. The standard deviation of these output measurements includes the uncertainty arising from the variability of the timer and the shutter movement, as well as the true variations in the output rate. If the relative standard deviation is larger than about 0.5%, further tests should be made to investigate (and if possible suppress) the source of the variability.

To estimate systematic effects (e.g. always starting too early or stopping too late), a series of irradiations of different duration should be made. A plot of the measured output as a function of irradiation time should be linear and pass through the origin. If this is not the case, the intercept with the abscissa represents a timing error and an attempt should be made to eliminate or minimize the effect, for example by adjusting the timing mechanism. If the effect cannot be eliminated, the remaining timing error should be taken into account in the calibration procedure or in the uncertainty budget.

5.3. COBALT-60 GAMMA RAY CALIBRATION LABORATORY

TRS-374 [1] included the possibility of using either ^{60}Co or ^{137}Cs sources for the calibration of ionization chambers. Since ^{137}Cs has been largely phased out for radiation therapy, this report considers only calibrations using ^{60}Co. Either an irradiator or a teletherapy unit can be used; in the latter case some modifications might be necessary to meet the requirements given in this section.

With regard to the contents of Section 5.1 describing the equipment required for an X ray calibration laboratory, a ^{60}Co beam requires no transmission monitor or filtration and the beam shutter (or source movement) will form part of the installation. The requirements regarding the ionization chamber support and positioning are similar to those for an X ray laboratory (see Section 5.1.5).

5.3.1. Radiation source

For convenience, the activity of the source should be sufficient to produce an air kerma rate of not less than 0.1 Gy/min at a distance of 1 m. For ^{60}Co, this implies a minimum activity of the order of 20 TBq, or 40 TBq if this minimum air kerma rate is to be achieved at the end of a five year half-life of ^{60}Co.

The radioactive impurity content (isotopes other than ^{60}Co) should be as low as possible. Contaminants with a different spectrum from ^{60}Co might have an impact on the calibration coefficient. Contaminants with a different half-life from ^{60}Co might affect calibrations to the extent that a half-life correction is applied. Long term measurements will give an indication of the effective half-life of the source.

To minimize scatter in the source capsule and to minimize the width of the penumbra of the beam, the source capsule should be as small as possible while achieving the required activity. However, for most commercially available irradiation facilities, the choice of radiation sources that can be used with the facility is normally very limited.

5.3.2. Collimator

The collimator defines the size of the radiation field in the plane of measurement. Commercially available teletherapy units are normally equipped with a variable collimator. In routine use for calibrations the same standard field size is always used and the adjustment mechanism of the collimator should be blocked or disabled to avoid accidental adjustment of the field size. If for certain applications a different field size is used, there should be a method of mechanically verifying the return to the standard field size used for calibrations. A suitably machined reference block that just fits into the collimator when the correct field size is set serves as a convenient check.

5.4. CHARACTERIZATION OF A COBALT-60 FACILITY AND BEAMS

5.4.1. Leakage and stray radiation

For the determination of leakage and stray radiation of ^{60}Co units, similar statements as for X ray laboratories apply (Section 5.2.1). If the ^{60}Co unit contains a source that moves (rather than a shutter arrangement), the test for leakage radiation should be carried out with the source in the beam-off position and also in the beam-on position. For the test in the beam-on position, the main beam must be blocked, for example by means of a block of lead (of the order of 10 cm in thickness) positioned across the collimator.

The leakage and stray radiation should not exceed the limits specified by local or national regulations.

5.4.2. Determination of beam centre and field size

Unlike the situation for X rays, in which the beam defining diaphragm can be moved with respect to the X ray focus, in general there is no independent control of the individual collimator jaws and consequently

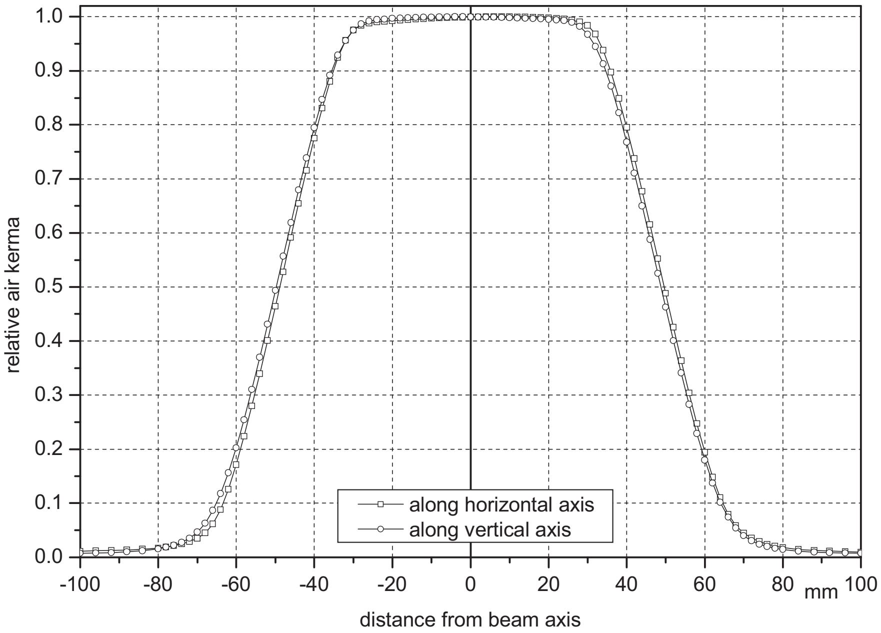

FIG. 6. Relative response of a small volume ionization chamber on orthogonal axes in the calibration plane. From these measurements the beam size, the beam centre and the beam uniformity can be determined.

no adjustment of the beam centre with respect to the source. As described in Section 5.2.2, to determine the beam axis at the calibration distance, the relative response of a small volume ionization chamber is measured on the horizontal and vertical axes. Example data for a ^{60}Co facility are shown in Fig. 6. From these data, the field size on each axis is determined as the distance between the two 50% points. The beam centre is defined by that point lying midway between the four 50% points, although several horizontal and vertical iterations might be required to locate this point. If the resulting field size is not that required, the collimator must be adjusted and the measurements repeated.

These data also give a measure of the beam uniformity and can be used to estimate the uncertainty arising from beam non-uniformity or to derive appropriate correction factors if necessary.

5.4.3. Output variations due to source movement

In many ^{60}Co units, rather than employing a beam shutter, the irradiation is controlled by means of a movement of the source between a shielded storage position (beam-off) and an irradiation position (beam-on). This movement can introduce variations of the output rate of more than 0.1% because of a failure of the source to stop always in the same position. The presence of such output rate variations should be tested by using a dosimeter controlled by a precision electronic timer, either internal or external, in order not to confuse source positioning uncertainties with the timing uncertainties discussed in Section 5.2.4.

To check for variations in source positioning, a first series of at least ten measurements of the output rate should be made with the source continuously exposed and using the electronic timer. This is an accurate method of determining the output rate. For a typical ^{60}Co gamma ray beam the standard uncertainty of the distribution of a series of about ten measurements should be small, usually less than 0.1% (after all necessary corrections are applied and assuming a measurement time of several tens of seconds).

A second series is then made with the source returned to its storage position between measurements. All measurements must start after the source is fully open and stop before the beam is switched off. The standard deviations of the two series of measurements should be calculated and compared. If the standard deviations differ by more than a factor of two it is unlikely to be due to random errors of measurement, and source positioning is probably the cause. If this variation is unacceptably large, experienced service personnel might be able to offer a solution. If no technical solution is available, the uncertainty due to this effect can be reduced by averaging over several (at least ten) calibration measurements with the beam switched off between individual measurements. Otherwise, the effect should be included in the uncertainty budget.

5.4.4. Timing uncertainties

Considerations regarding timing uncertainties for ^{60}Co gamma ray units are similar to those discussed in Section 5.2.4 for X ray facilities. It should be noted, however, that for ^{60}Co units in which irradiation is controlled by means of a movement of the source, uncertainties can arise from variability both in the timing of the source movements and in the position of the open source. Consequently, the measurement of the latter effect, described in the previous section, should be made before undertaking the measurement of timing uncertainties as described in Section 5.2.4. It is also of note that while variability in source positioning is a critical element that has an impact on all irradiations, source timing is only relevant when there is no electronic timer linked to the dosimeter.

5.5. LONG TERM STABILITY OF OUTPUT RATE

5.5.1. Routine consistency checks

Routine consistency checks can help identify possible problems or anomalies before they contribute to calibration errors. The output rate from a ^{60}Co unit is governed by radioactive decay, while that from a good quality X ray unit can be expected to be constant with time (for generating potentials above 20 kV). Both can be used for routine consistency checks. Each time measurements are carried out with the secondary standard for the purpose of calibrating a given beam, the measured output should be compared with that expected from previous measurements. A graphical presentation of the data will help to show possible trends.

Additionally, SSDLs could choose to maintain one or more good quality dosimeters that they calibrate on a periodic basis for the purpose of consistency checking. This makes it easier, in the event of an observed change, to demonstrate the stability, or otherwise, of the secondary standard.

A further opportunity for consistency checking is whenever a user chamber is recalibrated. In this case, historical data for that chamber should be examined to confirm that the new calibration data are consistent with previous results. The threshold for which an observed change deserves further investigation will depend on the user instrument and on the known reproducibility of calibrations at the SSDL, but is likely to be of the order of 0.2%.

In addition to routine consistency checks, the field size and beam centre should be remeasured periodically, perhaps once per year, as described in Section 5.2.2 for X rays and Section 5.4.2 for ^{60}Co. In the case of an X ray unit, the HVL should also be remeasured, at least for the lowest and highest generating potentials used for calibrations (see Section 5.2.3).

5.5.2. Problem diagnosis

Unexpected changes in the air kerma or absorbed dose rate can be due to many factors, and it is not possible to give an exhaustive list of the possible sources. Some of the first things to check are: the electrometer settings (polarizing potential, measurement range, capacitor); for X ray beams, the generating potential, tube current and beam filtration; the chamber position; the field size setting (collimator or diaphragm); the temperature and pressure readings, the normalization to standard temperature and pressure and other software corrections (such as the decay correction for ^{60}Co radiation).

If no explanation is found, the next step might be to repeat the measurements with a different chamber. If the anomaly persists, then a series of measurements could be made in a different beam. For example, if the change has been observed in an X ray beam, then measurements in a ^{60}Co beam should indicate whether or not the problem is with the radiation source or the measuring assembly.

If the anomaly is only present for an X ray unit, it might be that the beam quality has changed. This possibility can be checked by repeating the measurement of the HVL[1] for several beam qualities and comparing the results with historical values. A change in HVL at high generating potentials is likely to be due to a change in the applied potential. If there is evidence that the generator is no longer stable, it should be repaired before proceeding. A change in HVL only at the lowest generating potentials might be due to a change in the inherent filtration, for example from the accumulation of deposits on the X ray tube window.

If there is no evidence of a change in HVL, another possibility is a change in the tube current, or in the tube output because of changes to the surface properties of the anode. If possible, an independent measurement of the tube current should be carried out. If it has changed significantly, the power supply might need servicing. If the tube current is changed but stable, it is likely that the X ray unit can continue to be used once the beam output has been re-established using the secondary standard.

If the problem still cannot be identified, it will probably be necessary to measure beam profiles, as described in Section 5.2.2 for X rays and Section 5.4.2 for ^{60}Co, to check the beam alignment and field size. If either has changed significantly, the reason for the change should be identified. For an X ray unit, it could be that the position of one of the diaphragms has changed with respect to the tube. For a ^{60}Co unit, it might be that the source position has changed with respect to the collimator.

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[1] Alternatively, a filter whose transmission was established at the time of the original HVL measurement can be used as a rapid check of the beam quality.

6. CALIBRATION EQUIPMENT

6.1. SECONDARY STANDARD DOSIMETERS AND THEIR CHARACTERIZATION

An SSDL must have a secondary standard dosimeter that has been calibrated at the BIPM, at a PSDL or at the IAEA laboratory. This dosimeter should conform to the specifications given in Ref. [46] for reference class instruments. It is recommended that the secondary standard be recalibrated at intervals of about three years, although this period can depend on its demonstrated long term stability (see Section 6.1.7) and might therefore differ between instruments.

The secondary standard can be used either directly for routine calibrations of user instruments or periodically to calibrate one or more working standard instruments or to determine the air kerma or absorbed dose rate of a ^{60}Co unit for subsequent use in routine calibrations. The overall uncertainty attributed to the calibration of a user instrument might be slightly less when it is calibrated against the secondary standard rather than a working standard, but the difference should be small and must be balanced against the increased risk of damage or of a change in the calibration coefficient of the secondary standard if used regularly. It is emphasized that the dosimetry of an SSDL depends on the stability of the secondary standard and it is essential that it is maintained with the utmost care and stored in a safe place under stable environmental conditions that minimize the possibility of change in the calibration coefficient.

The ionization chamber of a secondary standard dosimeter must have a high degree of long term stability, only a modest energy dependence and must be vented (sealed chambers are generally less stable long term). For the measurement of air kerma, suitable buildup caps might be necessary. If the chamber is to be used in a water phantom, a waterproof sleeve must be available (unless the ionization chamber is designed so that it can be inserted directly into water). The same sleeve that was used for the calibration of the chamber in water should be used for all subsequent measurements using this chamber in water. The use of a thin synthetic rubber sheath is not recommended, as there is a greater risk of leakage, it might restrict pressure equilibration of the air in the chamber with the ambient air and it could contain atoms of high atomic number.

The measuring assembly (usually an electrometer) measures the charge or current from the ionization chamber. It often also provides the polarizing potential for the ionization chamber. The measuring assembly can either be calibrated together with the ionization chamber (the recommended method), or the two can be calibrated separately (see Section 7.1.3). In the latter case, the calibration of the measuring assembly in terms of electric current or charge must be traceable to primary standards of these quantities. It should be noted that when using a measuring assembly with autoranging, some charge can be lost as the instrument changes range. To obtain accurate readings, it is necessary to disable the autoranging feature and to select the range appropriate for the charge or current to be measured.

Special cables are necessary to connect the ionization chamber to the measuring assembly. In general, a high insulation coaxial cable will generate electrical noise whenever it is flexed or otherwise deformed. Although this will usually be short lived, it can give rise to errors if the cable is moved during a measurement. The cable might also generate a potential difference when it is strained; this could take some time to decay, during which time measurements might not be possible. The coaxial cable should therefore be of a non-microphonic or low noise type designed to minimize these effects.

In the following sections, measurements are described that are designed to improve the quality of and increase confidence in calibrations performed at the SSDL. The parameters described should be established before a new secondary standard dosimeter is used for calibrations and appropriate measurements should be made periodically to ensure that the dosimeter remains in good working order.

6.1.1. Leakage current

The leakage current of the secondary standard dosimeter before irradiation should be measured. As a general rule, it should not exceed 0.1% of the minimum ionization current to be measured. If the leakage current is too large, the electrometer leakage should be measured independently of the ionization chamber. If the leakage is not due to the electrometer it might be reduced by cleaning the connectors of the chamber and of the connection cable. A check should be made to confirm that this cable is not strained, deformed or otherwise damaged and is firmly connected.

A high leakage current can arise if a chamber has recently been irradiated, perhaps erroneously, without being connected to the electrometer. This can sometimes be remedied by disconnecting the chamber from its polarizing potential and briefly shorting the chamber connections. Other causes of leakage could be high humidity or, ultimately, damage to the ionization chamber.

Immediately following irradiation, the leakage current should be remeasured, ideally with an integration period of not more than 2 min. If this leakage value is also below the 0.1% limit given above, no further action is needed. Otherwise the chamber might not be suitable as a secondary standard.

6.1.2. Stabilization time

The measuring assembly requires a certain time after switching on before calibrations can be started, to permit temperature stabilization of the electronic circuits. Furthermore, the response of the ionization chamber might change for some time after irradiation has started or following a change to the polarizing potential or its polarity. This behaviour strongly depends on the ionization chamber type and might not be the same for individual chambers of the same type. While no general recommendations can be given, an example of the behaviour of a Farmer type NE2571 chamber in a ^{60}Co beam when the polarity of the chamber voltage is reversed is shown in Fig. 7 [50].

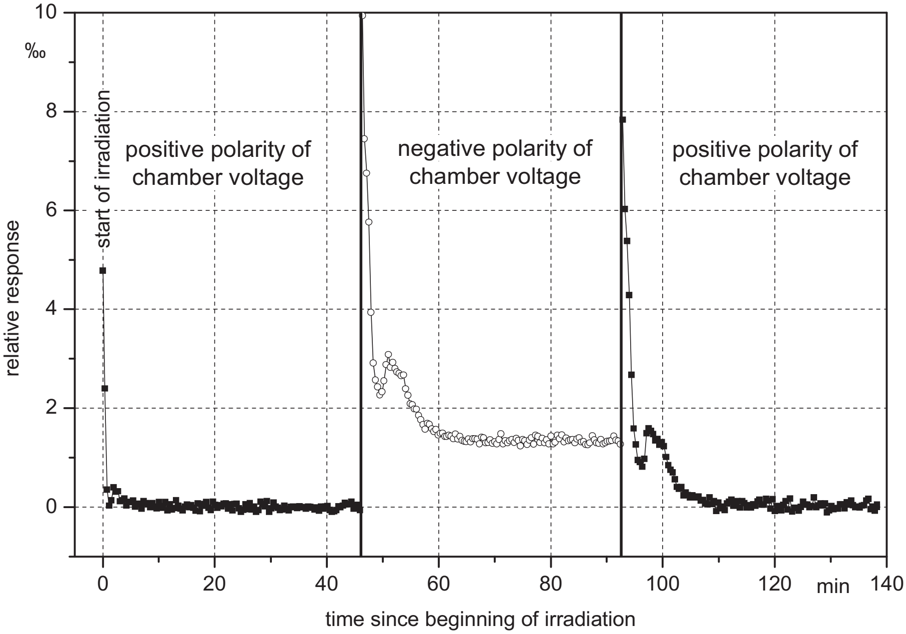

FIG. 7. Variation of the response of an ionization chamber of type NE2571 in a ^{60}Co beam after switching the beam on (with the polarizing potential applied earlier) and after changing the polarity of the polarizing potential (with the chamber continuously irradiated). The dose rate during this measurement was about 1 Gy/min.

To investigate the time necessary for the secondary standard to stabilize, the response should be measured until a stable state is reached. It should be noted that the stabilization time might depend on the dose rate, taking longer for lower dose rates, and so should be investigated under calibration conditions.

6.1.3. Polarizing potential and polarity

For a new ionization chamber, the choice of polarizing potential and polarity should follow any recommendations provided by the manufacturer, particularly in relation to the maximum operating potential. Some ionization chambers show a significant polarity effect (see, for example, Fig. 7), but this is not a problem if the chamber is always used at the same polarity and potential.

It is of course essential that the chamber be calibrated at the same polarity and potential as used subsequently. When communicating this information to the calibrating laboratory, it is important to specify not only the polarity and potential, but also the sense in which it is applied [51]. For example, when selecting a potential of +300 V, certain electrometers apply this potential to the chamber wall, with the central collecting electrode remaining at virtual ground potential. Other electrometers apply this potential, or the opposite potential, to the collecting electrode, the chamber wall remaining at ground. If the ionization chamber is calibrated with its own electrometer, then no confusion should arise as long as the correct polarity is selected. However, if the chamber is calibrated separately, using the electrometer of the calibrating laboratory, the sign and magnitude of the applied potential when using its usual electrometer must be determined and communicated to the calibrating laboratory. This can be measured at the electrometer connector using a digital multimeter, or determined from the information supplied by the manufacturer.

The polarity effect is unlikely to change with time unless a chamber has been damaged. Therefore, it is normally measured only for a new or newly repaired chamber, or to confirm that a chamber has not been damaged. The polarity effect can depend on polarizing potential, beam quality, field size and dose rate, and it might also be different for individual chambers of the same type. It is usually not larger than about 0.2%. Care must be taken during measurement to ensure that the chamber response has stabilized following each change of polarity; this can take up to 30 min (see Fig. 7). Failure to do so will result in an erroneous and misleading determination of the polarity effect. To ensure that any measured effect is not due to drift in the output rate, the polarity should be alternated at least twice.

6.1.4. Ion recombination

As a result of the recombination of ions before they can be collected, the response of an ionization chamber can change with electric field strength (an effect proportional to the polarizing potential, referred to as initial recombination) and with ion density (an effect proportional to dose rate and field strength, referred to as volume recombination) [52]. Initial recombination need not be considered, as it is the same at the calibrating laboratory and the SSDL. Volume recombination is generally very small for continuous (non-pulsed) beams at the output rates available in an SSDL [53]. In addition, if the output rate at the calibrating laboratory is similar to that at the SSDL, the effect will largely cancel. In general, therefore, no ion recombination correction need be applied. This assumes, of course, that no such correction was applied by the calibrating laboratory. This should be stated on the calibration certificate.

In the event that a measurement of ion recombination is desired, for example for very high output rates, the method of De Almeida and Niatel [54] can be used, as described in Ref. [55].

6.1.5. Directional dependence

While the directional dependence of a reference ionization chamber is likely to be small in a ^{60}Co beam, this is not the case, for example, in 100 kV X rays. It is therefore important always to position the chamber in the same orientation relative to the beam direction. Typically, the serial number or some other identifying mark is positioned to face the radiation source. The same orientation must be used for the chamber calibration and its subsequent use.

In this respect, care should be taken to ensure that the part of the chamber stem on which the identifying mark is inscribed does not loosen with age and become free to rotate. This has been known to happen for certain chamber types commonly used as reference instruments and can be the explanation for an observed change in chamber response in 100 kV X rays that is not evident in ^{60}Co gamma rays.

For measurements in water requiring a waterproof sleeve, the same consideration regarding orientation should be applied to the sleeve. Typically, an identifying mark is made on the sleeve and positioned to face the radiation source.

6.1.6. Electrometer calibration

6.1.6.1. Charge or current calibration

While the charge or current calibration of the secondary standard electrometer might well have been determined during calibration at the PSDL, the SSDL should have the facilities to check it periodically. The readout is commonly a digital display indicating the charge accumulated in a capacitor (charge measurement) or the voltage drop across a precision resistor (current measurement). The calibration for charge measurements can be checked by injecting a known charge using an external calibrated capacitor (ideally an air capacitor) and voltage source. The voltage source can be either a precision power supply with a known voltage or a stable power supply measured with a high quality laboratory standard voltmeter. The calibration for current measurements can be checked using an accurate, high impedance, constant current source. The reference scale reading chosen for the charge or current calibration should be one half to two thirds of the full scale. The result of this measurement is a calibration factor that strictly applies only at the reference scale reading of the range calibrated.

6.1.6.2. Range change factors

For multirange instruments, the calibrated values at the reference scale reading for each range calibrated can be expressed in terms of range change factors. These factors are evaluated relative to a range chosen as the reference range. The range change factor is therefore, by definition, unity for the reference range.

6.1.6.3. Linearity

Modern digital voltmeters are accurately linear beyond the needs of dosimetry. However, there might still be analogue instruments in use whose scale is not adequately linear. Checking linearity consists essentially of determining the charge or current calibration for a series of scale readings, in addition to the reference scale reading, within each range of interest. However, for linearity measurements it is not necessary for the injected charge or current to be known in absolute terms; it is only necessary that the relative values be known with the desired accuracy. Linearity for each range can be expressed as a correction factor for non-linearity, evaluated for each of the series of scale readings relative to the reference scale reading. The non-linearity correction is therefore, by definition, unity at the reference scale reading. Measurements of linearity usually need only be carried out once for a given electrometer, as it is unlikely to change with time.

6.1.6.4. Loaded leakage

An additional measurement of interest is the loaded leakage. For an electrometer in charge mode, this is a measurement of the charge leakage when a significant charge is present on the capacitor. This can be determined by not clearing the electrometer after an irradiation and measuring the change in the charge reading over several minutes. The loaded leakage should not differ significantly from the usual leakage measurement (Section 6.1.1). If differences of more than a factor of 2 are observed, the electrometer might need servicing.

6.1.7. Stability and maintenance

The long term stability of the secondary standard dosimeter, in addition to being established by its calibration history, is also verified implicitly during the routine measurements of output rate described in Section 5.5.1. These together form a stability check system that incorporates redundancy, with components that include a ^{60}Co unit, one or more X ray units and associated monitor chambers, one or more working standard dosimeters and any other secondary standards locally available.

Additionally, a portable radioactive source can provide a useful independent stability check. A check source is normally designed for a particular type of ionization chamber, and detailed information on its use should be provided in the instruction manual. The temperature in the check source at the position of the ionization chamber should be measured and the chamber reading corrected accordingly. The reading must also be corrected for radioactive decay to a chosen reference date. (A check source must not be used for instrument calibrations.)

All measurements with the secondary standard, whether to establish stability or as part of regular laboratory procedures, must be performed strictly according to documented laboratory protocol and the results recorded and retained in a form that permits the ready assessment of instabilities and drifts. A graphical presentation of such data is particularly helpful in identifying drifts. If no discrepancies are found using such a system incorporating redundancy, a high degree of confidence can be placed on the conclusion that the secondary standard is stable (at the stated level of uncertainty).

On the contrary, if any component of the system shows a significant change, the discrepancy must be investigated immediately. The advantage of redundancy is that it permits an instability in the secondary standard to be distinguished from an instability in one of the elements of the check system. In the event of failure of such an element, the aim should be to rectify the problem and to re-instate the element in question, or if need be replace it, so that the long term integrity of the check system is not compromised.

If at any time it is suspected that the secondary standard has suffered damage, or if the stability check system shows that the calibration coefficient has changed by more than around 0.3% from the value assigned at the most recent calibration, the instrument should be sent for repair and/or recalibration as soon as possible.

6.2. ANCILLARY EQUIPMENT

In addition to the secondary standard dosimeter, a number of other items of equipment are essential in the operation of calibration services at an SSDL. New items of equipment should not be put into service until they have been properly tested and, where applicable, calibrated; some items will need long term constancy checks. The SSDL should maintain an inventory of all equipment contributing to its calibration services, in which each item is uniquely identified and its history maintained. The original document should be safely stored in a master file, with working copies available in the appropriate laboratory[2]. These documents should contain at least the following information:

(a) Description of the item and date of purchase;
(b) Manufacturer, model and serial number;
(c) Maintenance information (regular checks and repairs undertaken and parts replaced).

Items requiring periodic calibration should include the following additional information:

(i) Calibration interval, date of current calibration and due date of next calibration;
(ii) Calibration history, ideally in graphical form;
(iii) Reference to where the details of the calibration procedure can be found.

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[2] This holds also for information stored in computer files. Special care must be taken to avoid accidental deletion or modification of the data.

In maintaining the quality of calibration services, it is desirable to establish a system for calling timely attention to items requiring periodic calibration to ensure recalibration within the specified interval. The interval should be chosen such that there is a high degree of confidence in the use of the instrument for calibrations. The calibration history of the instrument, where it exists, is useful in assessing the suitability of the calibration period.

When calibration or checks on SSDL equipment are carried out elsewhere, the SSDL needs to be satisfied that these are appropriate and competently carried out. Such calibration procedures and test methods should be fully documented for reference in the SSDL.

A general principle for reliability in the work of any calibration laboratory is maintaining a reasonable degree of redundancy. When practicable, there should be more than one item of each type of equipment and more than one method of making important measurements.

6.2.1. Working standards and other dosimeters

As noted in Section 6.1, it is normally not advisable to routinely use the secondary standard. Working standards, calibrated within the SSDL against the secondary standard, should be available for use in routine calibrations. Other suitable dosimeters, such as transfer or field instruments, might also be needed for general use by the SSDL, for example for measurements of HVL and field uniformity, for research or training programmes, or for measurements at other institutions.

6.2.2. Voltage sources

The secondary standard, working standards, monitor chamber and some instruments received for calibration might include power supplies for the ionization chamber polarizing potential, but it is unlikely that all instruments to be calibrated as well as those used for commissioning and other activities will incorporate a power supply. It is therefore likely that stable voltage sources with an appropriate range (typically up to 500 V) will be necessary at some stage, and it is prudent to have one or more such sources readily available.

While the calibration status of a voltage source used to apply an ionization chamber polarizing potential will be included in any quality system, this is not a critical component because the response of an ionization chamber is relatively insensitive to the absolute value of the polarizing potential. Rather, it is the stability of the source that is important.

6.2.3. Timers

In certain situations, for example dosimetry using TLDs, a timer might be used with the shutter to control and measure the irradiation time (the use of the shutter to control irradiation time is discussed in Section 5.2.4). Alternatively, an external timer might be used to control the integration time of an electrometer, leaving the beam on continuously. For such applications an electronic timer is recommended and a relative standard uncertainty of time measurements of not worse than 0.1% should be achieved.

Electronic timers with an internal oscillator are very accurate and essentially independent of fluctuations in the mains frequency. However, timers that are essentially synchronous clocks (that depend on the mains frequency) and manual stopwatches are less reliable and can give rise to both random and systematic errors. They should be checked periodically (say, at least once a year) against a time signal of known accuracy.

Errors due to the operator can be significant if timing is carried out with a stopwatch. Such errors can mask small changes in instrument performance. It is not advisable to use a stopwatch to determine times of less than 5 min.

6.2.4. Distance and depth measuring devices

Appropriate devices such as callipers should be available for setting and measuring distances and depths. For measurements in air, it should be possible to set the distance from the source to the chamber with a reproducibility of better than 0.5 mm.

When a phantom is used, it should likewise be possible to set the distance from the source to a reference surface of the phantom with a reproducibility of better than 0.5 mm, and furthermore position the ionization chamber in the phantom, with respect to this surface, with a reproducibility of better than 0.5 mm. For a vertical beam, the phantom must be filled so that the height of the water surface with respect to this surface is known.

6.2.5. Water phantom

For calibrations in terms of absorbed dose to water a suitable phantom must be available. The use of a cubic water phantom with plastic walls and a side length of approximately 30 cm is recommended, consistent with the phantoms typically used for the calibration of secondary standards. In horizontal beams, the entrance surface incorporates a window larger than the beam and typically not more than around 5 mm in thickness.

6.2.6. Thermometers

An SSDL should possess a high quality reference thermometer, ideally a mercury in glass thermometer, with a calibration certificate traceable to a primary standard of temperature. This thermometer should span the temperature range from –0.5°C to +30°C, with a resolution of 0.2°C or better. The reference thermometer should be kept as the laboratory standard. Its calibration should be checked about once a year using an ice bath. If an error is found, the thermometer should be sent for recalibration, unless it is of the mercury in glass type, in which case an additive correction should be applied over the entire range of the thermometer.

For routine measurements, other thermometers, such as mercury in glass thermometers, thermistors, platinum resistance thermometers or electronic temperature recorders, should be used. These are calibrated over the temperature range of interest by comparison with the reference thermometer in a stirred water bath. The frequency of recalibration is determined by experience and depends on the particular type of thermometer used. Mercury in glass thermometers, while intrinsically stable and reliable, are fragile and should be protected from shock, which might break the mercury column.

A digital temperature recorder continuously monitoring and recording the laboratory temperature can be helpful.

6.2.7. Barometers

A barometer capable of measuring the atmospheric pressure with a calibration uncertainty of 0.1% or better is required. The barometer must have a calibration certificate traceable to a primary standard of pressure. The recommended type is a mercury precision barometer. This barometer type does not need recalibration as long as the mercury surface remains clean and the meniscus remains sharp and easy to read.

If aneroid or electronic barometers are used, they should be calibrated at least once a year. This can be done either by a calibrating laboratory traceable to a primary standard of pressure, or at the SSDL by comparison with a local mercury barometer. Note that if the barometer under calibration has an adjustment to set the reading to the calibrated value, this device must be resealed after adjustment.

In use, a barometer should be placed at approximately the same height as the ionization chambers during calibration, either in the irradiation room or in a neighbouring room in which the air pressure is the same (the rooms being connected, for example, by cable ducts).

A digital pressure recorder continuously monitoring and recording the pressure of the ambient air in the laboratory can be helpful.

6.2.8. Hygrometers

The response of an ionization chamber is relatively insensitive to the humidity of the ambient air, and hence a hair hygrometer is sufficiently accurate for laboratory use. If the relative humidity is between 20% and 80% at the usual operating temperatures, no humidity correction is required. Outside of this range, it is possible to derive a correction (normally to 50% relative humidity) by making use of the data given in figure 5.14 of Ref. [56].

However, because of a possible increase in leakage current, ionization chambers should not be used in an environment where the relative humidity is above 75%. Furthermore, storage under conditions of high humidity should also be avoided. If it is not possible to store chambers in an environment where the relative humidity is acceptable, desiccants should be used to keep chambers dry. However, when stored with a desiccant, a chamber response might show some drift when first used and must be allowed to stabilize before measurements are made.

In addition, the calibration of a hair hygrometer is liable to change if it is subjected to very high or very low humidity. Such an instrument should therefore be checked occasionally (e.g. against a whirling-arm hygrometer) and adjusted accordingly.

6.2.9. Other items of equipment

There are many other items of equipment that might be of use at different times in the routine operation of an SSDL. The following shortlist of items might be considered essential:

(a) A computer system to collect and analyse data and to prepare calibration certificates and other documents;
(b) A multimeter;
(c) A micrometer for measuring the thickness of filters and absorbers;
(d) Radiation protection survey meters to measure leakage and stray radiation from radiation sources and radiation levels in occupied areas;
(e) Access to the services of a machine shop for the construction and modification of laboratory equipment.

7. FUNDAMENTALS OF CALIBRATION

7.1. CALIBRATION METHODS

7.1.1. Calibration by substitution or tip to tip

In calibration by substitution, the reference point of each chamber is placed successively at the measurement point. Note that the reference point of a cylindrical or thimble ionization chamber is located on the chamber axis at a distance from the tip either as stated by the manufacturer or as indicated on the instrument. For a plane parallel chamber, the reference point is normally taken to be at the centre of the inner surface of the front window (for the thin window chambers used for low energy X rays, the outer surface is taken). In X rays, calibration by substitution normally requires a monitor chamber (Section 5.1.4).

In tip to tip calibration, the two ionization chambers are placed coaxially with the ends of the chambers close to each other and irradiated simultaneously. If either sensitive volume has a length much greater than its diameter or if measurements are being carried out in a phantom, it might be better to place the chambers side by side with the chamber axes parallel (still referred to as tip to tip calibration). In both cases, the reference points of the two chambers should be positioned symmetrically with respect to the beam axis and at the same distance from the radiation source.

Conventional X ray tubes usually have reflection targets (in contrast to the transmission targets used with accelerators, for example). As a result, there can be a significant variation of output rate and photon energy along the cross-section of the beam parallel to the anode–cathode direction of the X ray tube (the heel effect). For tip to tip calibration in X rays, therefore, the reference points of the two chambers should be positioned on a line perpendicular to the anode–cathode direction. To compensate for any residual radial non-uniformity of the beam, the measurement should be repeated with the chambers interchanged in position and, if time allows, the positions should be interchanged several times. The mean of the calibration coefficients obtained with the chamber in the two positions should be taken as the best estimate.

In tip to tip calibration, each chamber receives scattered radiation from the other. The error introduced by this effect is minimized when the two chambers are similar in design. Tip to tip calibration might be considered the method of choice in X ray beams if there is no monitor chamber or if it has become unreliable.

7.1.2. Calibration in air or in a phantom

Calibrations in terms of air kerma are carried out in air. The chamber support should be such that scattered radiation is avoided or minimized (Section 5.1.5) and the temperature sensor should be positioned just outside the radiation field. For ionization chambers other than thin window parallel plate chamber types, the walls of the chamber must be thick enough to establish electron equilibrium at the radiation qualities used. For X ray beams, the chamber wall is usually sufficiently thick for this purpose, but for ^{60}Co gamma ray beams a buildup cap will almost always be necessary.

Calibrations in terms of absorbed dose to water are carried out in a water phantom. Care should be taken that the chamber is either waterproof or is used with its waterproof sleeve. Since the same sleeve that will be used for the calibration should be used for all subsequent measurements in water, SSDLs should encourage the user to send a sleeve with the chamber. It is recommended that the sleeve be made of PMMA with a wall thickness not more than 1.5 mm.

For cylindrical and thimble chamber types, the sleeve should allow the chamber to slide with ease to touch the bottom and to be removed without force, but without undue freedom, and should not interfere with air pressure equilibration within the chamber. The use of a thin rubber sheath is not recommended as there is a greater risk of a water leak and the sheath might restrict pressure equilibration. Parallel plate chambers can also be used if the chamber is inherently waterproof or supplied with a waterproof enclosure, which should be made of PMMA with no more than 1.5 mm of added material in front and behind. The chamber and sleeve should not be left in water longer than necessary to carry out the measurement.

After filling, the water temperature should be allowed to equilibrate. Typically, 30 min will be sufficient. The temperature of the air in the chamber should be taken to be that of the water in the phantom. Owing to evaporation from the water surface, there will be a vertical temperature gradient within the phantom and the temperature should be measured at approximately the same height as the chamber; the measured temperature will be lower than the room temperature by typically about one degree. This effect can be reduced in horizontal beams by placing a thin plastic film over the easily accessible areas of the water surface.

During this period of temperature equilibration, and for horizontal beams, there is likely to be an outward movement of the entrance window, leading to an increase in the chamber depth. Conversely, in a vertical beam, evaporation will cause the chamber depth to decrease. These effects should be measured and the chamber depth adjusted accordingly before calibration measurements begin.

7.1.3. Assembly or component calibration

In an assembly calibration, the complete dosimeter (i.e. the ionization chamber connected to its electrometer) is calibrated in grays per scale division. In a component calibration, the ionization chamber is calibrated separately from its electrometer and the overall calibration is derived from a radiation calibration of the ionization chamber in grays per coulomb and a charge calibration of the electrometer in coulombs per scale division.

The choice of which type of calibration to make depends on a number of factors. For the calibration of a single dosimeter at a single radiation quality, assembly calibration might be less time consuming. For calibrations involving several beam qualities or several ionization chambers using the same electrometer, component calibration is likely to be more efficient, particularly if the local electrometer and data collection system are automated. Component calibration is also advantageous in the event of poor performance as it provides information on the behaviour of the ionization chamber and the electrometer separately. Particular care, however, must be taken regarding the polarity of the polarizing potential, as certain electrometers apply this potential to the collector. If this is not clear from the instruction manual, it might be necessary to contact the user (see Section 6.1.3 for a discussion of problems related to polarity).

Other constraints might be the unavailability of suitable adapters or, for certain older electrometers, an inability to separate the ionization chamber from its electrometer, both of which demand an assembly calibration. In the event that transportation of the electrometer is problematic, only the ionization chamber can be calibrated. In all cases, it is important to ensure that the dosimeter is operated according to the instruction manual.

7.2. PRE-CALIBRATION MEASUREMENTS

The following describes a series of preliminary tests to be performed to ensure that the dosimeter and all associated items of equipment are suitable for calibration. TRS-374 [1] recommended that a portable check source provided by the user should be measured at the SSDL. However, security concerns have made the shipment of radioactive sources difficult and it is no longer practical to recommend portable check source measurements at the SSDL. Nevertheless, the SSDL should encourage users to use a local radioactive source to check the response of their dosimeter just before sending the instrument for calibration and soon after receiving the instrument back. As portability is no longer a requirement, these stability measurements can be made using a fixed source, for example a ^{60}Co unit if available.

7.2.1. Preliminary checks on user equipment

(a) Check that all accessories, such as waterproof sleeves, buildup caps and protective caps for high insulation connectors, are present.

(b) Examine the ionization chamber, electrometer, cables and connectors for signs of damage. If the ionization chamber is to be calibrated separately, check that there is no shortcircuit between the collecting electrode and the chamber wall, or between either of these and the guard.

(c) Switch on the electrometer and check that it operates correctly when put through the recommended measurement sequence.

(d) Allow the dosimeter to stabilize for a few minutes after switching on the polarizing potential, then measure the leakage current for several minutes by switching the instrument to the measure condition with no radiation present and with the chamber connected as for normal measurement. If the leakage is greater than the limit claimed by the manufacturer (or, if no limit is given, about 0.2% of the scale reading that would be obtained during the calibration procedure), examine the cable connectors for signs of damage or contamination. If necessary, clean the connectors carefully and repeat the leakage test. If the leakage remains high, but has approximately the same value (this value not being greater than around 1%), it should be possible to proceed with calibration. The leakage will be remeasured following irradiation; if the values obtained for the pre- and post-irradiation leakages are similar, the calibration remains valid. If the leakage is large and variable the dosimeter is probably damaged and will have to be repaired.

Do not embark on the calibration procedure unless the dosimeter has been shown to pass the tests listed above. If the instrument does not pass these tests, contact the user and discuss what action is appropriate. Do not try to repair the instrument, other than cleaning the connectors, without the formal approval of the user.

7.2.2. Pre-irradiation and stabilization time

Stabilization time refers to the time taken for the dosimeter to settle down after being subjected to a change, such as switching on or changing the polarizing potential, or being moved (particularly the coaxial cable). Such changes can result in a temporary change in sensitivity. These considerations are similar to those described for the secondary standard in Section 6.1.2. Example data following a polarity change (for a secondary standard) are shown in Fig. 7.

Another aspect of stabilization is a change in sensitivity for the first few readings after switching on the beam. This is a highly variable effect; a series of nominally identical chambers can behave differently in this respect. It is therefore good practice to pre-irradiate a chamber to a suitable dose (perhaps several grays) before making measurements. This pre-irradiation is normally carried out in parallel with the switching on of the polarizing potential.

Owing to these effects, calibration should not begin until the instrument has stabilized. If a suitable time is recommended in the manufacturer's instruction manual, this should be followed and considered a minimum. Operator experience with the chamber type in question can be of help. However, the most reliable procedure is to measure the chamber response at regular intervals until a stable state is reached. An example of a stability measurement for a user chamber is given in Fig. 8.

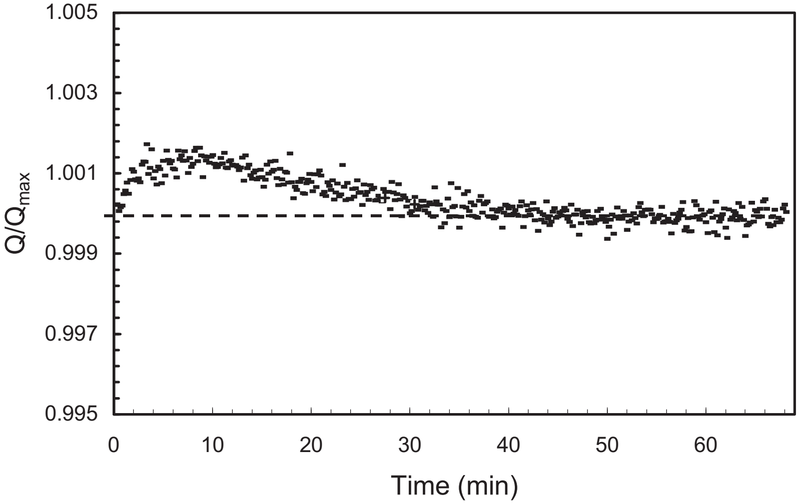

FIG. 8. Stabilization time for a Keithley 6517 electrometer with a PTW 23333 ionization chamber. In this example, acceptable stability is achieved after about 30 min, which represents a total dose of around 5 Gy.

7.3. EXAMPLE OF AN ASSEMBLY CALIBRATION

The details of a given calibration procedure depend on the radiation type, the ionization chamber and electrometer types, and might follow common practice specific to the SSDL. While it is impossible to provide a set of detailed procedures, there are certain common elements that are likely to apply in every case. The example considered here is the assembly calibration of a dosimeter in terms of absorbed dose to water in ^{60}Co gamma rays. This is perhaps one of the more difficult calibrations because it is carried out in a water phantom, but it is also one of the more important because it is the basis for most radiotherapy dosimetry.

The first step is to assemble and check the necessary equipment. The water phantom will need to be positioned on the axis in front of the ^{60}Co source. The collimator setting (field size) should be checked and adjusted if necessary (Section 5.3.2). Using appropriate positioning equipment, the distance from the water phantom to the ^{60}Co source must be accurately set. Typically, this will be achieved using a mechanical device that is referred in some reproducible way to the ^{60}Co unit and to a reference point or plane of the phantom, but other approaches, for example optical, can be used. Assuming a source to surface distance of approximately 1 m, an uncertainty of 0.5 mm in the phantom position will contribute an uncertainty of about 0.1% to the calibration coefficient.

The reference point of the ionization chamber to be calibrated must be positioned at the measurement point within the water phantom, oriented as specified by the user. This can be done with or without water in the phantom, depending on the measurement device used. For a cylindrical chamber, the reference point of the chamber is taken to lie on the central axis of the chamber, while for a parallel plate chamber, the reference point is at the centre of the inside surface of the entrance window. Typically, the reference depth in ^{60}Co is 5 cm of water (expressed as 5 g/cm^2 when the phantom has a plastic window) and given that the dose gradient is about 0.5%/mm, the chamber should be positioned with an uncertainty of less than 0.2 mm if the positioning uncertainty is not to contribute more than 0.1% to the calibration coefficient. For the reasons outlined in Section 7.1.2, the depth will need to be checked and if necessary adjusted after the water temperature has been allowed to stabilize.

The chamber should be connected to the electrometer and the polarizing potential applied as specified by the user. (For a new or newly repaired chamber, the user might request a measurement of the polarity effect; see Section 6.1.3.) It should be confirmed that the equipment for measuring the water temperature and the air pressure is available and working correctly. The chamber leakage current should be checked (before the beam is switched on) and the chamber pre-irradiated until its response is stable. This will only be known after several sets of readings have been accumulated (see Section 7.2.2).

A suitable electrometer range should be chosen, with any autoranging disabled, along with an irradiation time that will give a reasonable electrometer reading. This will typically lie between 20 s and 100 s, but will depend on the chamber volume and the activity of the ^{60}Co source. The pre-calibration leakage should be measured, a series of ten readings made and the mean and standard deviation of the mean computed. This should be repeated for at least three more sets of ten readings, with the temperature and pressure noted for each set and each mean value normalized to the standard conditions of temperature and pressure chosen for the calibrations. The post-calibration leakage should be remeasured and the mean values corrected using the average of the pre- and post-leakage measurements.

For a good quality dosimeter, the normalized mean values, corrected for leakage, should be consistent to better than 0.2%, and the standard uncertainty of the overall mean should be below 0.1%. If so, one can proceed with confidence to derive a calibration coefficient, the first step of which is to correct the overall mean value to the chosen reference time using the adopted ^{60}Co half-life. If M is used to denote the corrected dosimeter reading per unit time and D_{w} denotes the absorbed dose to water per unit time at the reference point, derived from the secondary standard and corrected to the same reference time, the dosimeter calibration coefficient is obtained from:

$$N_{D,\mathrm{w}} = D_{\mathrm{w}}/M \tag{6}$$

The SSDL must also estimate the uncertainty of the calibration coefficient. Typically, this estimate will be the same, or very similar, for all well behaved dosimeters. Some assistance on constructing a suitable uncertainty budget is given in Section 8.

7.4. ELECTROMETER CALIBRATION

When a component calibration is made, the user electrometer is calibrated separately from the ionization chamber. If suitable facilities are available at the SSDL, and when the instrument to be calibrated is of high quality and sufficient importance, this might involve the charge or current calibration of several or all ranges, as well as measurements of linearity for these ranges. Charge and current calibrations, linearity measurements and the equipment required to make them are described in Section 6.1.6.

Section 6.1.6 also describes the expression of the results of these measurements, for each range calibrated, in terms of a calibration factor determined at the reference scale reading and non-linearity correction factors for a series of scale readings. For multirange instruments, the results for different ranges are expressed in terms of range change factors, relative to a range chosen as the reference range. The range change factor is, by definition, unity for the reference range.

This information is relatively complex and should be presented on the calibration certificate in a manner that is clear to the user. Furthermore, the estimated uncertainty for each stated value should be given. A simpler approach, suitable for well behaved electrometers for which all correction factors are close to unity, is to state on the calibration certificate that all corrections are negligible at a stated level of uncertainty. This approach should only be chosen if it cannot give rise to a dosimetric error that exceeds 0.5%.

7.5. CALIBRATION CERTIFICATES

The results of each calibration carried out by the SSDL must be reported accurately, clearly and objectively on a calibration certificate. While the most important information on a calibration certificate is a list of calibration coefficients with their uncertainties, additional information is necessary for the correct interpretation and subsequent use of the calibration results. The calibration certificate obtained from the BIPM, the PSDL or the IAEA SSDL could be used as an example when the SSDL designs its own calibration certificate.

If more than one dosimeter is calibrated for a given user, a separate certificate should be issued for each dosimeter. The information that shall be contained in a calibration certificate is specified in the international standard ISO/IEC 17025 [5]. The following list of items is an interpretation of these general requirements for the calibration of dosimeters:

(a) A title (e.g. Calibration Certificate).
(b) Name and address of the calibrating laboratory.
(c) A unique certificate number, printed on every page.
(d) Date of issue of the certificate.
(e) Page number on every page, in the form “Page x of y”.
(f) Name and address of the user.

(g) Unique identification of the instrument(s):
  (i) Manufacturer, model and serial number (ionization chamber and electrometer);
  (ii) Other items used (buildup caps, waterproof sleeves).

(h) Date of calibration measurements and staff performing calibration.

(i) Results of the calibration (preferably in tabular form):
  (i) Beam quality specifier (HVL, gamma ray source);
  (ii) Calibration coefficients, stating quantity and unit;
  (iii) Uncertainty of measurement and coverage factor.

(j) Reference conditions:
  (i) Calibration distance and depth (if relevant);
  (ii) Chamber orientation and field size;
  (iii) Reference values of temperature, pressure and humidity.

(k) Calibration conditions:
  (i) Range of actual values of temperature, pressure and humidity;
  (ii) Air kerma or absorbed dose rate.

(l) Instrument operation:
  (i) Reference settings:
    — Polarizing potential of the wall relative to the collector;
    — Range;
    — Scale reading;
    — Position of any other relevant switches;
  (ii) Stabilization time;
  (iii) Pre-irradiation time or dose.

(m) Calibration procedure:
  (i) Type of calibration (substitution or tip to tip);
  (ii) In air or in a phantom (with phantom material and size);
  (iii) Assembly or component calibration;
  (iv) Reference point of chamber;
  (v) Orientation of chamber;
  (vi) Use of a buildup cap or waterproof sleeve.

(n) Results of additional measurements:
  (i) Leakage current;
  (ii) Scale non-linearity factors;
  (iii) Range change factors;
  (iv) Polarity effect.

(o) Information about the beams:
  (i) Generating potentials;
  (ii) Filters and inherent filtration (if relevant).

(p) Miscellaneous information:
  - (i) Traceability of the calibration;
  - (ii) Name, position and signature of the responsible person.

7.6. QUALITY CONTROL IN CALIBRATION PROCEDURES

In Section 7.2, recommendations are given for work that should be carried out before calibrations start, to ensure that all the equipment is in good working order. Additionally, it is good practice to build some self-consistency checks into the calibration procedure. These might include the following:

(a) Have critical elements of the experimental arrangement checked by a second person;
(b) During the measurement procedure, confirm that the results do not show any significant trend;
(c) Verify that the repeatability of successive readings is within expected limits;
(d) Compare the results with previous calibrations of the same dosimeter, if available, or with other dosimeters of the same type;
(e) Compare the results with those for the same dosimeter in a different beam, if available, for example evaluate the ratio $N_{D,\mathrm{w}}/N_{\mathrm{K}}$ and compare this with the results for chambers of the same type;
(f) If time permits, repeat the calibration.

8. EVALUATING THE UNCERTAINTY

8.1. GENERAL ASPECTS OF UNCERTAINTY ESTIMATION

In addition to determining and reporting the calibration coefficient for a dosimeter, the SSDL is also expected to evaluate and report the uncertainty of the calibration coefficient. It is often the case that the evaluation of the uncertainty of a measured quantity is more difficult and time consuming than the measurement itself. However, for routine calibration in terms of a given quantity of similar, well behaved instruments in a particular beam, the uncertainty can be expected to be about the same for all instruments. Hence some initial effort must be invested to evaluate the uncertainty of a given calibration procedure (e.g. calibrating a dosimeter in terms of air kerma in a ^{60}Co beam).

Despite the fact that the uncertainty does not need to be re-evaluated for each subsequent calibration using that procedure, those responsible for carrying out the measurements and producing calibration certificates should nevertheless be aware of the quantities that contribute significantly to the uncertainty. If a particular calibration is anomalous (as a result, for example, of an unusually large chamber leakage current), the calibration staff should be able to decide whether or not the uncertainty should be increased in this case, or indeed whether or not the calibration can proceed with acceptable uncertainty.

The ISO document Guide to the Expression of Uncertainty in Measurement [6] (commonly referred to as the GUM) was developed to provide general guidelines for evaluating and expressing uncertainties. Although it provides worked examples, there are none that are specific to the work of SSDLs. To provide additional guidance to the SSDLs, the IAEA produced a publication entitled Measurement Uncertainty: A Practical Guide for Secondary Standards Dosimetry Laboratories [8]. This report provides detailed examples that can be followed by the SSDLs in generating uncertainty estimates. It considers all of the quantities that might contribute to the overall uncertainty and neglects those that contribute less than 0.1%. It then chooses typical values for the uncertainties of the remaining quantities (typically about 15 quantities) and shows how to evaluate the overall uncertainty.

On first sight, both the GUM and the IAEA publication can appear imposing because of the extensive use of mathematics and statistical terms. Despite this appearance, the assessment of uncertainties is not an exact science; this perspective is well summarized by a statement in the ISO guide:

> “Although this Guide provides a framework for assessing uncertainty, it cannot substitute for critical thinking, intellectual honesty and professional skill. The evaluation of uncertainty is neither a routine task nor a purely mathematical one.”

The stated uncertainty is a statement of how well the SSDL has determined the calibration coefficient. Although mathematics can help in evaluating the uncertainty, the SSDL needs to be comfortable that it represents a realistic range within which the calibration coefficient should lie. One useful consistency check is to compare the uncertainties reported by different SSDLs or the IAEA for the same calibration procedure. These data are available in the on-line CMCs [7] of Appendix C of the CIPM MRA. If the uncertainty reported by one SSDL for a given procedure is significantly different (say, by more than 30%), it might be instructive to examine the source of the difference.

8.2. EXPANDED UNCERTAINTY

It has become common practice in calibration certificates to state the expanded uncertainty corresponding to a confidence interval of approximately 95%. This is achieved by multiplying the standard uncertainty by a coverage factor k. The relationship between k and the confidence interval is complex, but in most cases the appropriate expanded uncertainty can be obtained by multiplying the standard uncertainty by $k = 2$. This should be made clear in the calibration certificate. For the example given in Table 2, the inclusion of the following statement would be appropriate:

> "The expanded uncertainty corresponding to a confidence interval of approximately 95% is obtained by multiplying the standard uncertainty by the coverage factor $k = 2$ and is equal to 0.8%."

8.3. EXAMPLE OF AN UNCERTAINTY BUDGET

Staff members at the SSDL are encouraged to study the GUM [6] and the IAEA publication [8]. However, they might find it useful to consider an example that does not make use of a particularly sophisticated analysis, but nevertheless provides a satisfactory evaluation of the uncertainty when calibrating a dosimeter against a secondary standard for air kerma in a ^{60}Co beam. Such an example is presented in Table 2. Although the values for uncertainty components used here are typical, the SSDL should consider each item within the context of their own laboratory and calibration procedures.

Each uncertainty component is discussed according to its item number:

(1) When the SSDL has its secondary standard dosimeter calibrated, it will be issued with a calibration certificate containing a calibration coefficient and its uncertainty. This uncertainty might be expressed either as a standard uncertainty, in which case the values used in Table 2 are taken directly from the certificate, or as an expanded uncertainty with coverage factor $k = 2$, in which case the values must be divided by this factor and the results used in the present table.

(2) Over time, and perhaps from experience with similar chambers, the SSDL will accumulate data on the stability of its secondary standard dosimeter. This value might be the result of an analysis of repeat calibrations over a long period (which results in a Type A estimate), but where fewer data are available could be little more than a reasonable guess (a Type B estimate as given in the table).

TABLE 2. TYPICAL UNCERTAINTY BUDGET FOR THE CALIBRATION OF A GOOD QUALITY IONIZATION CHAMBER AGAINST A SECONDARY STANDARD FOR AIR KERMA IN ^{60}Co GAMMA RAYS

Item	Source of uncertainty	Relative standard uncertainty (%)	
		Type A	Type B
	Reference air kerma rate		
1	N_K of secondary standard (BIPM/PSDL/IAEA)	—	0.2
2	Long term stability of secondary standard	—	0.2
3	Positioning of secondary standard chamber	—	0.02
4	Source decay	—	—
5	Temperature and pressure correction	0.03	0.1
6	Measurement of current	0.05	0.1
	Calibration of user chamber		
3	Positioning of user chamber	—	0.02
5	Temperature and pressure correction	0.03	0.1
6	Measurement of current	0.05	0.1
	Quadratic summation	0.08	0.35
	Combined standard uncertainty	0.36	

(3) Both the secondary (or working) standard chamber and the chamber to be calibrated must be positioned at the reference point. With care, a chamber distance can be set to better than 0.1 mm, so that for a reference distance of 1 m the positioning uncertainty is usually very small.

(4) In terms of the measurement protocol, it is assumed here that the SSDL only uses its secondary (or working) standard occasionally to calibrate the field produced by the ^{60}Co source, so that in principle there is a component of uncertainty arising from the uncertainty of the half-life of ^{60}Co. In practice, however, this uncertainty is negligible.

(5) Air temperature and pressure influence the response of both the secondary (or working) standard and the chamber under calibration. The effect of the calibration uncertainty of the temperature sensor and the barometer is usually negligible. Uncertainty in the air density is generally dominated by the difficulty in determining to what extent the temperature measured at the sensor represents the temperature of the air in the cavity. In Table 2, a Type B uncertainty of 0.1% has been assigned largely to reflect the fact that these two temperatures could differ by up to 0.5°C. The Type A uncertainty of 0.03% is obtained from the standard deviation of repeat measurements of the air density correction under conditions where the temperature and pressure are stable.

(6) The ionization current is typically read using an electrometer that measures the charge accumulated over a well defined time. The uncertainty of the time measurement makes no significant contribution to the uncertainty of the current determination. In Table 2, a Type B uncertainty of 0.1% has been assigned to the stability of the electrometer calibration and the Type A uncertainty of 0.05% is the standard uncertainty of the mean of repeat measurements of the ionization current.

The combined uncertainty of 0.36% is obtained by summing the individual components in quadrature (the square root of the sum of the squares). In this case, the SSDL might choose to report a standard uncertainty of 0.4% on all of its ^{60}Co air kerma calibration coefficient.

9. QUALITY SYSTEM FOR SECONDARY STANDARDS DOSIMETRY LABORATORIES

9.1. QUALITY POLICY AND OBJECTIVES

The delivery of reliable calibrations requires trained staff, suitable equipment and adequate resources. There is a growing international consensus that a formal system devoted to quality assurance can benefit both the calibration laboratory and its customers. In the broadest sense, a quality system consists of a documented set of rules and procedures; although it might appear to be an extra-administrative burden, it can have a number of benefits. In fact, most SSDLs will already have some system in place for ensuring quality, although it might not be formally documented, nor correspond to the requirements of a modern quality system. The purpose of a quality system in a calibration laboratory is to maintain, and where possible improve, the reliability of calibrations. The documentation should be seen as a tool to achieve this purpose, not the purpose itself.

For the SSDL, documented calibration procedures reduce the likelihood of error following a change in staff. If an error is made, it should be easier to find the source if all laboratory work is carried out using standard, documented procedures, and having found the source a modification of the procedure should reduce the possibility of the same error being made in the future. Having standard calibration procedures will reduce the tendency for staff to take shortcuts, which might compromise a calibration result. With standard procedures for receiving and shipping instruments, there is less chance of equipment being damaged or misplaced.

For the user, there is added confidence in the results received from an SSDL if it is known that it has a quality system in place. The users will be able to trace more easily the status of their calibration request, they will receive a standardized calibration certificate and they will know that there is a formal mechanism for dealing with a complaint in the event of a problem with the calibration.

An important element of a successful quality system is the commitment of the laboratory management. Recognition of its importance implies that adequate personnel and resources will be made available to develop and maintain the quality system. The SSDL management should develop a written quality policy that includes a general statement regarding its commitment to provide users with calibration services of the highest quality. Specific commitments should be made regarding:

(a) Maintaining qualified, competent and well trained calibration staff;
(b) Maintaining equipment, resources and an environment suited to providing high quality calibrations;
(c) A regular review of the quality system to identify possible areas for improvement.

The following sections identify some of the key components of a quality system that every calibration laboratory should try to implement. The quality system is intended to build on the procedures already in place in the SSDL and should not impose an undue burden on laboratory resources. While every SSDL would be expected to implement an appropriate quality system, its scope and contents should be adopted to fit the services and the resources of the laboratory. The quality system must reflect the organizational specificity, directives and policies pertinent to each SSDL and cannot simply be copied from other organizations. Nevertheless, many features of the quality system can be identified that are common to other laboratories with similar tasks, equipment and responsibilities.

9.2. PRINCIPAL DOCUMENTATION

In general, producing documentation can be time consuming and is often left as the last task of a project, or is not done at all. Documentation for a quality system is no exception, but a common misconception is that a lot of material must be generated. This should not be the case, and often it is simply a matter of refining existing documentation or writing down basic procedures. A quality system is not intended to be a substitute for knowledgeable and well trained staff. Instead, it is to provide assurance that staff with the same skill set will carry out procedures in the same way, and that procedures will continue to be carried out in this way if for some reason staff members change. Cooperative and open dialogue with staff during the preparation of the documentation will ensure a positive environment for the development of an SSDL quality culture.

The structure of the quality documentation is not a key aspect of the process, but a coherent approach to its structure facilitates its reading and understanding by staff and users. It is generally recommended that the documentation be structured in a logical hierarchy, starting with a high level document, sometimes called a quality manual, followed by a series of standard operating procedures, technical instructions, forms and reports. This systematized presentation makes it easier to manage the overall quality system documentation.

9.2.1. Quality manual

The quality manual is the highest level document in the quality system. In addition to containing a statement of the laboratory quality policy, it should address at least the following items:

(a) The laboratory management structure, with identification of those who have responsibility for ensuring that the quality system is used and maintained;
(b) The mechanisms for assessing, reviewing and updating the quality system;
(c) The procedures for receiving, tracking and shipping equipment;

(d) The procedures for generating and approving standard operating procedures, instructions, forms and reports.

Additional details regarding the quality manual can be obtained from ISO/IEC 17025 [5].

9.2.2. Standard operating procedures

Standard operating procedures describe the important steps to be followed for each calibration step. Since calibrations are carried out by well trained staff, the corresponding operating procedure need not contain excessive detail, and often one or two pages will be adequate. It is the responsibility of the staff involved to identify and describe those steps that can have an important impact on the outcome of the calibration.

9.2.3. Technical instructions

Technical instructions provide detailed information on the operation and use of all relevant equipment and on the preparation and handling of items for calibrations and related activities. It might be appropriate to incorporate selected parts of equipment manuals or other existing documentation into technical instructions. Examples include descriptions of check source measurements, perhaps extracted from the operating manual, and HVL measurements.

9.2.4. Forms and reports

Forms are pro-formas to be completed by calibration staff or users as part of the calibration procedure. An example might be a calibration request form, completed by the user, or an instrument reception form, completed by calibration staff. A report is generally the output from some part of the calibration process. An example might be the measurement data output from the controlling computer.

The most important report is the calibration certificate, which is the means by which the SSDL transmits its measured calibration coefficients to the user. Although each certificate will contain specific information regarding the dosimeter being calibrated, the basic structure of the certificate should be the same for all users and dosimeters. The key information that should be included in a calibration certificate is listed in Section 7.4.

9.3. SUPPLEMENTARY DOCUMENTATION

This section lists some additional information that an SSDL might wish to include as part of its quality system documentation.

9.3.1. Equipment calibration and testing

In addition to one or more secondary standard dosimeters that have been calibrated against a primary standard, an SSDL will have many other items of equipment whose calibration status can impact on the result of a calibration. Examples include thermometers and barometers used to measure ambient atmospheric conditions. The individual calibration of such instruments is addressed in Section 6.2. The quality system should contain a documented schedule for checking the calibration of this equipment to ensure that calibrations and tests are carried out in a timely manner and that equipment remains in good working order.

9.3.2. Training needs and records and staff authorizations

Well trained staff is a critical component of a successful SSDL. Documentation describing the minimum training requirements for staff involved in a particular calibration activity helps to ensure that important qualifications are maintained when staff change. A regular, documented review of qualifications and training needs can also help to ensure that personnel are aware of new equipment and techniques as well as safety issues.

Quality system documentation should include a training record for each staff member. Depending on the size of the SSDL and the range of calibration services offered, documentation might also include staff authorizations (i.e. a list of the tasks that each staff member is authorized to perform). In this respect, it is good practice in the event of unplanned absences to have more than one staff member authorized to carry out each task.

9.3.3. Software

Software plays an important role in instrument calibration, data analysis and report generation. Some software components may have been generated by the laboratory, while others are based on packages available commercially. Unexpected errors can be introduced in many ways and software control is a notoriously difficult aspect of quality systems.

Nevertheless, some of the more common errors can be avoided by relatively simple measures. One such error is the use of the wrong version of a particular software code. Another is failing to adequately check the output from commercial software or from a modified in-house code. Documented procedures on how software is operated, updated, tested, stored and archived will help to eliminate these errors.

9.4. INTERNATIONAL GUIDANCE

The ISO, in cooperation with the IEC, has developed a standard (ISO/IEC 17025) [5] entitled General Requirements for the Competence of Testing and Calibration Laboratories, which describes the requirements a laboratory must meet to receive ISO certification.

A key aspect of ISO/IEC 17025 is the establishment of a quality management system within the calibration laboratory. ISO/IEC 17025 often refers to this 'quality management system' as the 'management system', but it should not be confused with the usual meaning of laboratory management, which identifies staff with responsibility for such matters as personnel and finance. Instead, ISO defines the quality management system as "the quality, administrative and technical systems that govern the operations of a laboratory" and it can be thought of as the system put in place to manage quality.

The formal procedure for establishing and maintaining accreditation according to ISO/IEC 17025 is complex and requires a considerable investment on the part of the laboratory. Some SSDLs have opted for, and achieved, formal accreditation. If the laboratory has the resources and the support of management then formal accreditation according to ISO/IEC 17025 should be encouraged. In this case, the laboratory should consult the ISO/IEC 17025 standard [5] for detailed guidance. For others, formal accreditation might not be achievable and indeed might not be necessary for the laboratory to maintain a reliable calibration service. In this case, the guidelines provided earlier in this section will help the SSDL establish the key elements of a quality system.

For those who intend to proceed with formal accreditation with a view to listing their CMCs on-line in Appendix C [7] of the CIPM MRA [4], the first requirement is that the SSDL is a signatory (or a designated institute) of the CIPM MRA. The CIPM MRA is discussed in Section 2.2 and provides two options for establishing a recognized quality system.

The first option applies to an SSDL that has established a quality system that meets the requirements of ISO/IEC 17025. In this case, the SSDL can be assessed by an accreditation body that fulfils the requirements of ISO/IEC 17011 [57]. Once accreditation is achieved, the SSDL may submit its CMCs to the appropriate RMO for review and transmission to the JCRB. After interregional review and possible modification, the CMCs will be listed in appendix C of the CIPM MRA.

The second option applies to an SSDL that chooses a different way of assuring quality or chooses a different quality system, or chooses to use ISO/IEC 17025 but without third party assessment. Such an SSDL may also submit its CMCs to the local RMO for review and transmission to the JCRB as above. In this case, however, demonstration of competence and capability might require visits and the examination of procedures by an NMI and/or by peers selected by the local RMO.

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