IAEA-TECDOC-1079

Calibration of brachytherapy sources

Guidelines on standardized procedures for the calibration of brachytherapy sources at Secondary Standard Dosimetry Laboratories (SSDLs) and hospitals

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FOREWORD

Brachytherapy techniques for treatment of female gynaecological cancers have been in practice ever since the discovery of radium. In 1972, the IAEA in co-operation with WHO formed an 'International Working Party for the Early Diagnosis and Treatment of Carcinoma of Cervix in Developing Countries'. This group did considerable work in promoting the use of safer radionuclides, such as ^{137}Cs, ^{60}Co and ^{192}Ir in place of ^{226}Ra and ^{222}Rn and in replacing the preloaded type applicators with the afterloading techniques, either manual or remote controlled. As these developments led to an overall improvement in radiation safety, the brachytherapy techniques became increasingly popular. Today, irradiation by brachytherapy is considered an essential part of the treatment for almost all the sites of cancer. With the improved localization techniques and treatment planning systems, it is now possible to have precise and reproducible dose delivery. However, the desired clinical results can only be achieved with a good clinical and dosimetric practice, i.e. with the implementation of a comprehensive quality assurance (QA) programme which includes detailed quality control procedures. As summarized in the present report, accidents in brachytherapy treatments have been caused due to the lack of traceable calibration of the sources, due to the incorrect use of quantities and units, or errors made in the dose calculation procedure. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources has established a requirement on the calibration of sources used for medical exposure. For sources used in brachytherapy treatments, a calibration traceable to a standards dosimetry laboratory is required.

The present report deals with the calibration of brachytherapy sources and related quality control (QC) measurements, QC of ionization chambers and safety aspects related to the calibration procedures. It does not include safety aspects related to the clinical use of brachytherapy sources, which have been addressed in a recent IAEA publication, IAEA-TECDOC-1040, "Design and Implementation of a Radiotherapy Programme: Clinical, Medical Physics, Radiation Protection and Safety Aspects". The procedures recommended in this report yield traceability to internationally accepted standards. It must be realized, however, that a comprehensive QA programme for brachytherapy cannot rest on source calibration alone, but must ensure QC of all the equipment and techniques that are used for the dose delivery to the patient. Therefore, a proper QA programme must also include QC of applicators, localization techniques, treatment planning systems, dose calculation method, facility design, treatment units, ionization chambers, etc. A comprehensive QA programme should help minimizing errors in the treatment planning and dose delivery. It also simplifies a meaningful intercomparison of the treatment results within the country and internationally. A detailed QA programme, both in therapy with external beams and with brachytherapy sources, has recently been given in the aforementioned publication of the IAEA. For brachytherapy, this programme addresses the different steps in a QA programme mentioned above.

The present publication incorporates the reports of several consultants meetings in the field of brachytherapy dosimetry. The main focus in this report is directed to the traceable calibration of brachytherapy sources, QC of the equipment used in the calibration and safety aspects related to the calibration procedure. In addition, a description of the activities at the IAEA Dosimetry Laboratory in the field of standardization of brachytherapy source calibrations, initiated on the basis of the consultants' recommendations, is given.

The IAEA staff members responsible for the compilation of this publication were H. Tölli and A. Shanta from the Division of Human Health.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

Brachytherapy uses encapsulated radioactive sources to deliver a high dose to tissues near the source. This form of therapy can only be safe and effective if the sources are calibrated and have a traceability to internationally accepted standards. For some brachytherapy sources, vendors assign large uncertainties to their stated calibration values, in some cases up to $\pm 10\%$. End-user calibration of brachytherapy sources is necessary, not only to check vendor stated calibration but to ensure traceability to internationally accepted standards. To quote the American Association of Physicists in Medicine (AAPM) report from task group 40 [1], "Each institution planning to provide brachytherapy should have the ability to independently verify the source strength provided by the manufacturer".

This report discusses calibration techniques of ^{137}Cs, ^{192}Ir, ^{60}Co and ^{125}I brachytherapy sources. The use of ^{60}Co high dose rate (HDR) brachytherapy sources is decreasing and also the number of brachytherapy units using ^{137}Cs HDR sources are limited. Therefore, in this report, emphasis is given to calibration of ^{137}Cs low dose rate (LDR) and ^{192}Ir LDR and HDR brachytherapy sources.

For ^{137}Cs LDR source calibrations, the IAEA Dosimetry Laboratory maintains reference sources calibrated at a Primary Standard Dosimetry Laboratory (PSDL). These sources can be used to calibrate well type ionization chambers maintained at the Secondary Standard Dosimetry Laboratories (SSDLs). On the other hand, no PSDL have standards for ^{192}Ir HDR source calibration. To obtain traceability also for these sources, a source must be calibrated using free in-air measurement techniques. The calibrated source is then used to calibrate a well type ionization chamber. This technique can also be used for calibration of ^{192}Ir LDR sources. The difference between ^{137}Cs LDR and ^{192}Ir calibrations is therefore in the free in-air measurements that are necessary in the latter case but can be avoided in the former case.

In Section 2 of this report, the sources and equipment for ^{137}Cs LDR calibrations are discussed in detail. The discussion is directed towards the equipment available at the IAEA Dosimetry Laboratory and the equipment that is necessary at the SSDLs in order to obtain traceability, via the IAEA Dosimetry Laboratory, in the ^{137}Cs LDR source calibrations. In Sections 3 and 4, calibration of ionization chambers, correction factors for both free in-air measurements and for well type ionization chambers for calibration of ^{192}Ir LDR wires are given. Finally, in Section 5, to maintain the quality in the calibrations, different steps in the QC of the sources and equipment are described.

1.1. Specification of brachytherapy sources

The recommended quantity for the specification of the gamma sources is the reference air kerma rate, defined by the ICRU [2, 3] as the kerma rate to air, in air, at a reference distance of one meter, corrected for air attenuation and scattering. For needles, tubes and other similar rigid sources, the direction from the source centre to the reference point shall be at right angles to the long axis of the source. The SI unit of reference air kerma rate is $Gy \cdot s^{-1}$ but for the purposes of source specification it is more convenient to use $\mu Gy \cdot h^{-1}$ for LDR brachytherapy sources, progressing to $\mu Gy \cdot s^{-1}$ and $mGy \cdot h^{-1}$ for HDR applications.

Many brachytherapy treatment planning systems use activity as the quantity for source specification. If the source is calibrated in terms other than activity, a conversion is necessary.

TABLE I. AIR KERMA RATE CONSTANTS FOR BRACHYTHERAPY SOURCES DISCUSSED IN THIS REPORT

Nuclide	Air kerma rate constant ($\mu Gy \cdot h^{-1} MBq^{-1} m^2$)
^{60}Co	0.3
^{137}Cs	0.077
^{192}Ir	0.108
^{125}I	0.033

The reference air kerma rate, expressed in $\mu Gy \cdot h^{-1}$, can be converted to activity using the air kerma rate constants given in Table I. The activity is then given in MBq. The values in the table are those recommended by the ICRU [3].

2. CALIBRATION OF REFERENCE ^{137}Cs SOURCES AT SSDLs

2.1. General

This section describes the procedures at the IAEA Dosimetry Laboratory and the SSDLs to standardize the calibration of the ^{137}Cs LDR brachytherapy sources. Two possible approaches can be considered for the calibration of these sources in terms of reference air kerma rate. The first approach requires reference sources to be calibrated by a standards laboratory and their use to transfer calibrations via well type ionization chambers. The second approach would be to do measurements with an ionization chamber which has an air kerma rate calibration that is traceable to a standards laboratory. The former method is similar to that used in the USA and some west European countries and also the method recommended by the consultants to be adopted by the IAEA in providing calibration service for ^{137}Cs LDR sources through the IAEA/WHO network of SSDLs. Calibration of brachytherapy sources by cavity ionization chambers is discussed in Section 3.

The recommended method is based on the acquisition by the SSDLs of sources and a well type chamber similar to those at the IAEA Dosimetry Laboratory. This method requires the SSDLs to calibrate their well type chamber at the IAEA Dosimetry Laboratory using the IAEA reference sources. The various steps involved in establishing a calibration chain for the LDR brachytherapy sources from the PSDL to the hospital users through the IAEA Dosimetry Laboratory are as follows:

— The IAEA has two ^{137}Cs brachytherapy sources, calibrated at a PSDL in terms of reference air kerma rate; the sources, together with a well type chamber, a large volume spherical chamber and an electrometer constitute the IAEA brachytherapy dosimetry standard.
— SSDLs acquire uncalibrated sources and a well type chamber similar to those at the IAEA; in addition, SSDLs must have at least one source of each type of the radionuclide for which user's calibration will be required. The whole set will constitute the SSDL brachytherapy dosimetry standard.
— The SSDL's well type chamber is calibrated at the IAEA Dosimetry Laboratory using the IAEA brachytherapy dosimetry standard.
— The SSDL measures the reference air kerma rate of its sources using the calibrated well type chamber.
— The SSDL calibrates user's sources and well type chambers using its standard.

2.2. Procedures at the IAEA Dosimetry Laboratory

2.2.1. Materials

2.2.1.1. The brachytherapy sources

The IAEA has purchased two types of ^{137}Cs brachytherapy sources from Amersham International. The sources are a CDCSJ5 type tube and a CDC1100 type miniature cylinder. The specifications of these sources are given in Table II.

TABLE II. BRACHYTHERAPY REFERENCE SOURCES AT THE IAEA DOSIMETRY LABORATORY

Radio-nuclide	Type	Code	Nominal activity (MBq)	Encapsulation (mm of SS)	Dimensions (mm) Length	Diameter
^{137}Cs	Tube	CDCSJ5	2313	0.5	20.0	2.65
^{137}Cs	Cylinder	CDC1100	3700	0.5	8.0	3.20

The sources have been calibrated in terms of reference air kerma rate at the National Institute for Standards and Technology (NIST), USA. The calibration of this type of sources at the NIST is done by direct comparison with their working standard sources using an ionization chamber at distances between 500 and 1000 mm [4]. The NIST working standard sources have been calibrated in air using the NIST cavity chamber exposure standards; these are absolute calibrations similar to those used for a ^{60}Co external beam calibration. The reference air kerma rate of the IAEA reference sources measured at the NIST, normalized as on 1st May 1996, are 339 $\mu Gy \cdot h^{-1}$ for the CDC1100 type source and 190.5 $\mu Gy \cdot h^{-1}$ for the CDCSJ5 type source, with an estimated uncertainty of less than 2% at the 95% confidence level.

2.2.1.2. Ionization chambers and electrometers

The IAEA has also purchased a well type chamber and an electrometer to standardize the measurement procedure and provide practical assistance to the SSDLs. The well type chamber, HDR-1000 Plus, is designed at the University of Wisconsin and manufactured by *Standard Imaging Inc.* The diameter of the chamber is 102 mm, its height 156 mm and with an active volume of 245 cm^3. Special inserts are provided for holding the sources, which are cylinders of diameter 35 mm and height 121 mm, with different inner diameters to suit different diameter sources. The outer aluminium wall of the chamber is 20 mm thick. The chamber has a vent hole to maintain the internal air at ambient atmospheric conditions. The electrometer used with the well type chamber is CDX-2000A, a digital portable instrument from *Standard Imaging Inc.*

The measurements in air are performed using a LS-01 ionization chamber, designed by the Austrian Research Centre and manufactured by PTW, Germany. The chamber is spherical in shape and has a volume of 1000 cm^3. The chamber wall is made of polyacetal resin (delrin) and is 3 mm thick. The outside diameter of the collecting volume is 140 mm. The central collecting electrode is spherical in shape and has a diameter of 50 mm. It is made of Styrofoam and is coated with graphite. Teflon is used as the insulating material. As the ionization current to be measured is of the order of a few pico amperes, a *Keithley-617* electrometer was used for the measurements in air. This electrometer is a highly sensitive instrument designed to measure voltage between 10 μV and 200 V, current between 0.1fA and 20 mA and charge between 10 fC and 20 nC.

For ease of handling, the sources were loaded into Perspex tube holders. The sources were then fixed in the holders using Perspex rods as illustrated in Fig. 1.

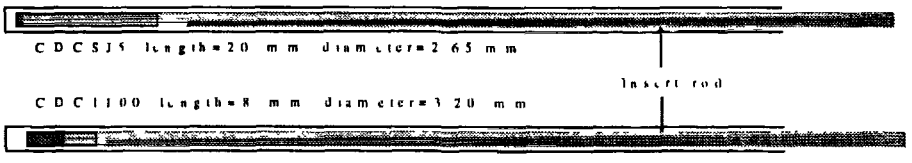

Figure 1. Perspex source holders. The sources are inserted in Perspex tubes of length 150 mm and held in a fixed position using insert rods.

2.2.2. *Methods*

2.2.2.1. Standardization of measurements with the well type chamber

An important aspect in the standardization of measurements with a well type chamber is the determination of the optimal position of the source within the chamber. With the source positioned at this point, the current is maximized and the uncertainty in the reference air kerma rate determination, due to positional uncertainty, is minimized. For the determination of the optimal position, measurements were made with the chamber positioned in the centre of the room (minimum distance from the walls was 1.5 meter) and at a height of 1 meter from the floor. Charge measurements were performed varying the position of the source along the axis of the chamber by inserting spacers of known length at the bottom, as illustrated in Fig. 2.

In all the measurements, the leakage current contributed less than 0.05% to the collected charge. The relative variation of the chamber response, normalized to the maximum value, is shown in Fig. 3. It can be seen that the maximum response of the well type chamber is obtained for the CDCSJ5 type source (total length: 20 mm) when a 39 mm spacer is inserted at the bottom of the well, whereas a 45 mm spacer is needed for the CDC1100 type source (total length: 8 mm). This means that the maximum response is obtained when the centre of the source is at about 50 mm from the bottom of the well cavity. The response decreases by about 0.5% for a shift of about 9 mm on either side of the position of the maximum response. In order to assess the long term stability of the set-up and the measuring devices, measurements in the optimal position were repeated during a long period. The chamber response was corrected for ambient conditions of temperature and pressure and the source decay using a half life for ^{137}Cs equal to 30.17 years (1 year = 365.25 days). The reproducibility of the well type chamber response over several months is illustrated in Fig. 4, where it can be seen that the variation is generally within ±0.5%.

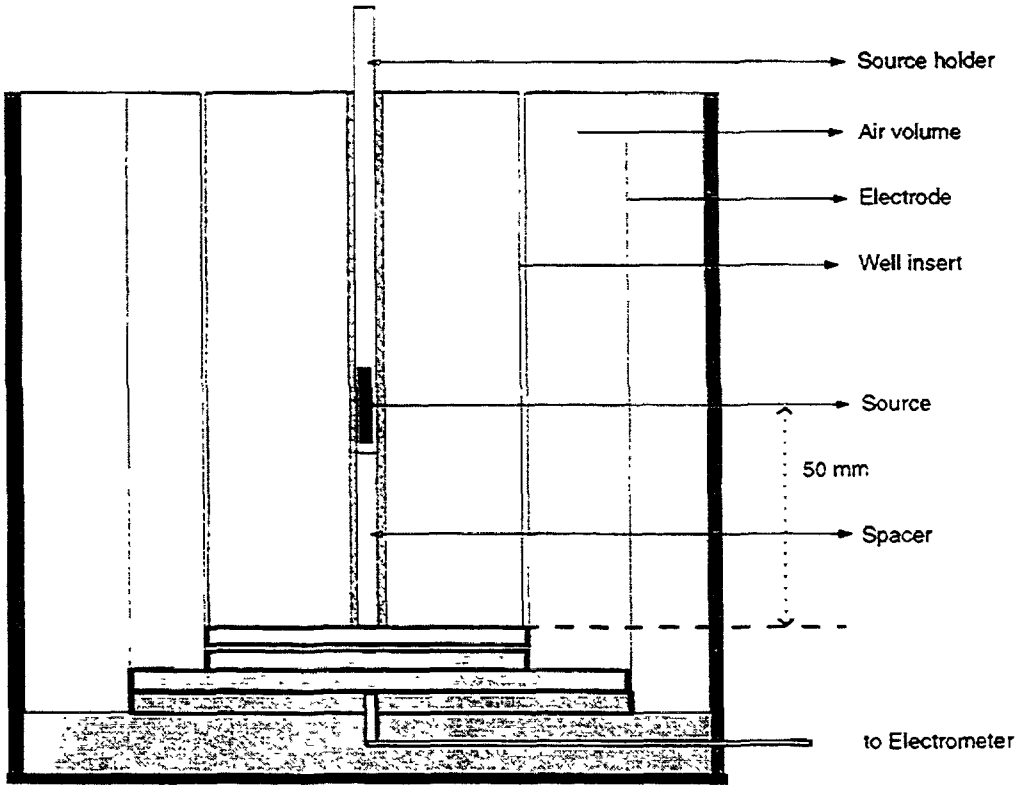

Figure 2. Positioning of the source and spacer in the well type chamber. The 50 mm distance indicates the optimum position for the source when using the IAEA Dosimetry Laboratory's standard well type chamber.

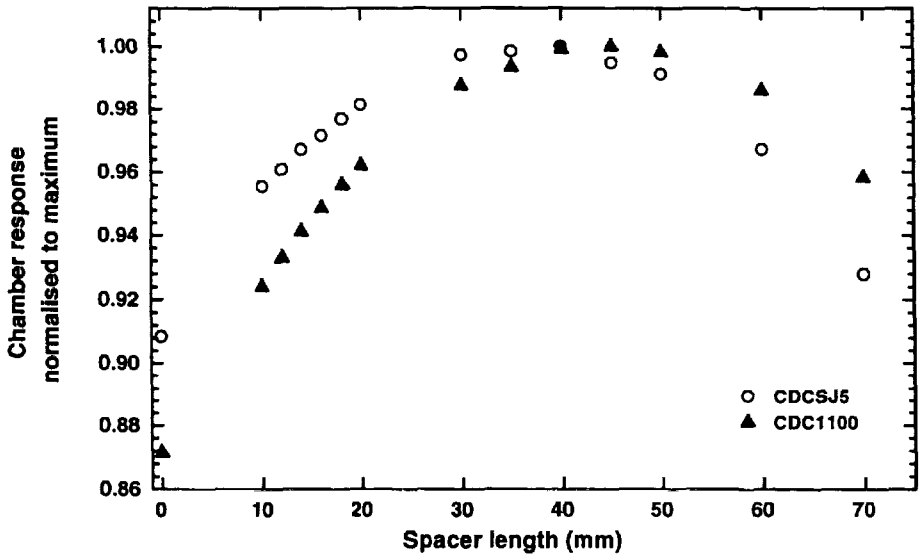

Figure 3. Variation of the response of the well type ionization chamber with the length of the spacer.

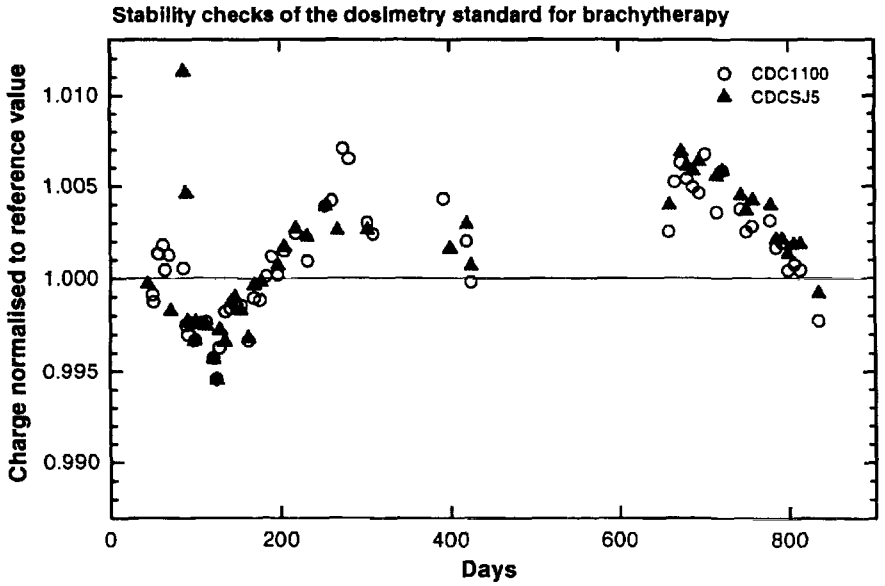

Figure 4. Stability of the well type chamber response. The variation of the response normalized to the reference value. The response is generally within ± 0.5%.

The reference air kerma rate calibration factor of the well type chamber, N_{K_R}, is determined from Ref. [5],

$$N_{K_R} = \frac{K_R \cdot t}{M_u \cdot k_{elect} \cdot k_{Tp} \cdot k_s} \qquad (1)$$

where

— K_R is the reference air kerma rate of the source;

— M_u is the electrometer reading of the charge collected by the well type chamber in time 't' [scale reading];

— k_{elect} is the calibration factor of the electrometer (nC/scale reading);

— k_{Tp} is the correction factor for the temperature (T) and pressure (p) at the time of the measurement, $k_{Tp} = \frac{273.15 + T}{293.15} \frac{101.325}{p}$; and

— k_s is the recombination correction factor [6].

2.2.2.2. Standardization of in-air measurements

The well type chamber can, in principle, be used only for the sources of the types for which it has been calibrated. In practice SSDLs will have to provide calibration of different types of sources to hospital users. The most appropriate approach for deriving a calibration is to compare the source to be calibrated with the reference standard in air at large distances, where the geometrical differences between the two type of sources are insignificant. The ratio of the reference air kerma rates of the sources is given by the ratio of the corrected readings. The purpose of the in-air measurements at the IAEA Dosimetry Laboratory has mainly been to assess the accuracy and reproducibility of such procedure before recommending it to the SSDLs.

A 1-litre spherical chamber (type LS-01) was used at source-to-chamber centre distances of 500 mm, 750 mm and 1000 mm. The geometry is illustrated in Fig. 5. Metallic rods, identical in size to the sources, were loaded in Perspex tubes identical to the type used for the sources. These dummy source holders were used for the alignment of the source and the LS-01 chamber for such in-air measurements. A Keithley-617 electrometer was used for these measurements and the leakage current was determined to be less than 0.1% for the lower-strength source at the largest distance. The short and long term stability of the measuring device and the reproducibility of the geometry were obtained by repeated measurements. The chamber response was corrected for the ambient conditions of temperature and pressure and for the decay of the source. The stability of the chamber response, normalized to the mean value over the period of measurements, is shown in Fig. 6 where it can be seen that the variation is generally within ±0.5%.

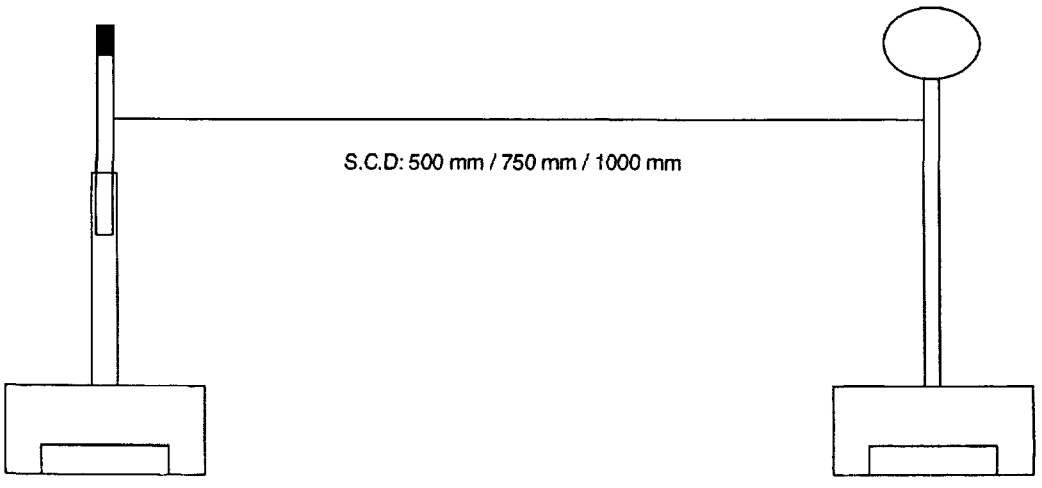

Figure 5. Alignment of the 1-litre spherical chamber (LS-01) and the ^{137}Cs source for the measurements in-air.

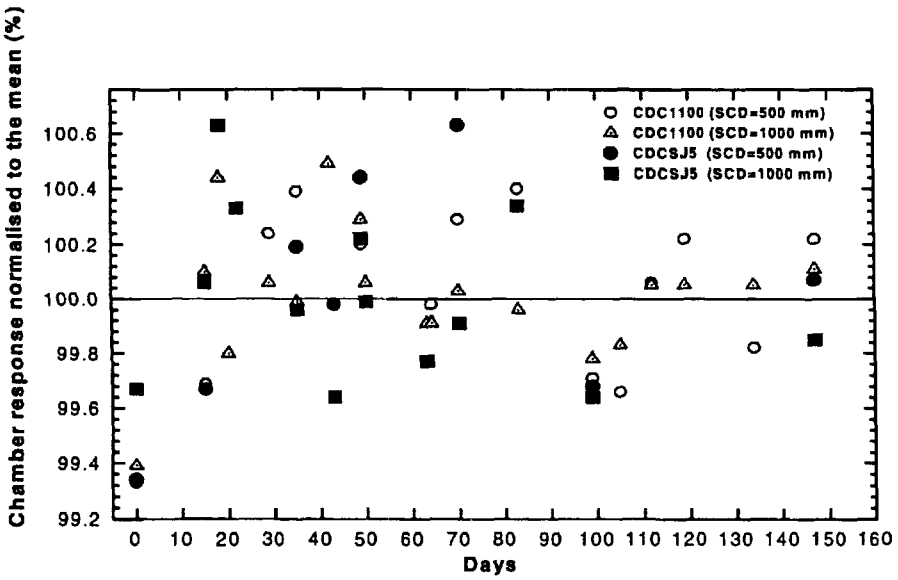

Figure 6. Reproducibility of in-air measurements at source-chamber distances of 500 mm and 1000 mm. The chamber response for each set of measurement was normalized to the mean response of the respective set over the period of measurement.

2.3. Estimation of uncertainties

The overall uncertainty in the calibration of the IAEA reference sources at the NIST has been quoted as 2% at the 95% confidence level, i.e. approximately 1% for one standard deviation. The addition of the uncertainty of the measurements at the IAEA Dosimetry Laboratory yields a combined uncertainty of less than 1.5% (1 standard deviation). Details on uncertainty estimation are given in Table III.

TABLE III. ESTIMATED UNCERTAINTIES (%) FOR THE CALIBRATION OF THE SSDL WELL TYPE IONIZATION CHAMBER AT THE IAEA DOSIMETRY LABORATORY

Uncertainty component	Type A	Type B
1. Measurements at the IAEA Dosimetry Laboratory:		
– source positioning in the well type chamber	0.04	
2. Charge measurement:		
– stability of the system (electrometer + chamber)	0.30	
3. Correction for influence quantities	0.2	
Recombination correction		0.1
Half-life of Cs-137		0.12
Impurity of the source		0.57
Square sum	0.13	0.35
Combined uncertainty, type A+B (1 standard deviation)	0.69	
4. Calibration of IAEA reference sources at NIST (type A+B)	1.00	
Total combined uncertainty, type A+B (1 standard deviation)	***1.21***	

Note: — The uncertainties for source position and stability are determined from a series of measurements made at the IAEA Dosimetry Laboratory.
— The uncertainty for the correction for influence quantities is taken from Ref. [7].
— The uncertainty in the half-life is given by the Nuclear Data Section of the IAEA.
— The uncertainty due to the impurity is taken as maximum probable presence of ^{134}Cs quoted by the supplier.

2.4. Procedures at the SSDLs

The general principles of the traceable calibration scheme and the technical provisions undertaken by the IAEA Dosimetry Laboratory for the development of the methods have been discussed thoroughly in Section 1. The present section will lay down in detail the recommended calibration procedures (methods and equipment) to be applied by the SSDLs. The SSDLs need to establish the traceability for their ^{137}Cs LDR standards to the PSDL via the IAEA Dosimetry Laboratory so that they in turn can continue the chain of traceability to the local hospitals.

The steps involved in transferring the calibration from the IAEA reference sources to the SSDLs sources may be summarized as follows:

— At the IAEA Dosimetry Laboratory, a calibration factor for the SSDL well type chamber (reference air kerma rate/scale reading) is obtained using the IAEA ^{137}Cs reference source(s).
— The SSDL measures the reference air kerma rate of local sources using its calibrated well type chamber under the same conditions used for the calibration at the IAEA. The source(s) thus calibrated will be the local standard and may be used by the SSDLs to provide calibration services to hospital users.

As with any other type of chamber calibration, measurements with a check source should be made at the SSDL before and after the calibration at the IAEA for checking the stability of their well type chamber. For all calibrations performed, either at the SSDL or in the hospital, the SSDL should ensure that the conditions of calibration as applied by the IAEA Dosimetry Laboratory are provided. In brief this means that all measurements should be done in a minimum scatter environment, with the chamber at least 1 m from any wall or floor. The chamber should be left to come to equilibrium with its surroundings before beginning calibration. The minimal time necessary for this is 30 minutes. A minimum of 4 significant figures should always be obtained for charge accumulated or current measurements. Thus charge should be accumulated for a set time depending on the activity of the source. A minimum of 5 measurements that are neither monotonically increasing nor decreasing should be obtained.

2.4.1. Materials

To achieve the traceability of calibrations with the minimum uncertainty, it is essential that the reference sources, source holders and handling devices acquired by the SSDL are of identical type to those used by the IAEA Dosimetry Laboratory (Table II). The source holders and spacers used for the calibration of SSDL's well type chamber at the IAEA Dosimetry Laboratory are provided to the SSDLs as part of the first calibration of the well type chamber.

The SSDL shall have a well type chamber of their own that should be calibrated by the IAEA Dosimetry Laboratory. It is recommended that the well type chamber is open to the atmosphere. If the chamber is sealed and the pressure of the gas is at a higher level than the ambient atmospheric pressure, it may develop a problem of slow leakage of the gas. In this case, a change in the calibration factor would result. Chambers open to the atmosphere need correction for temperature and pressure since the calibration factor is based upon a density of air corresponding to 20°C and 101.3 kPa.

It should be noted that the well type chamber and the electrometer have independent calibration factors. These calibration factors must be multiplied together to form the total calibration factor of the well type chamber and electrometer system. Unless the calibration

factor for the whole system is provided by the IAEA Dosimetry Laboratory, the calibration factor of the electrometer must be determined separately by the SSDL, e.g. by comparison with other electrometers using a constant current source.

2.4.2. Methods

2.4.2.1. Calibration of SSDL reference sources

If the well type chamber is different than that used by the IAEA Dosimetry Laboratory, the response curve will not necessarily be the same as that in Fig.3 and the SSDL should determine its characteristics. In addition, the ion recombination correction for the chamber must be determined.

The SSDL should calibrate its ^{137}Cs reference source using the calibrated well type chamber. The reference source is loaded in the perspex tube and secured in position using the insert rod, provided by the IAEA Dosimetry Laboratory. The source is then calibrated by inserting it along with the appropriate spacer, also provided by the IAEA, in the well type chamber insert so that the centre of the active portion of the source is located at the point of calibration. The reading, corrected for temperature and pressure and multiplied by the well type chamber calibration factor given by the IAEA Dosimetry Laboratory, will give the reference air kerma rate for the SSDL reference source.

2.4.2.2. Calibration of hospital's well type chamber

When the hospital's well type chamber is calibrated at the SSDL, it is done using the SSDL reference source. At first, a response curve for the hospital's chamber must be determined. Then the source is inserted in the hospital's chamber at the point of maximum response of the chamber. The correction for ion recombination for the hospital's chamber must be determined and accounted for if necessary. If the hospital's well type chamber is open to the atmosphere, the reading must also be corrected for the temperature and pressure. A calibration factor is then determined for the well type chamber in terms of reference air kerma rate per unit current. The current is normally measured by accumulating charge in a given time.

The hospital's well type chamber should be calibrated at the SSDL. However, if the calibration of the hospital's well type chamber by the SSDL is performed in a hospital, the SSDL well type chamber and/or reference sources must be transported. For safety reasons, the transport of sources is not generally recommended. Upon arrival at the hospital, all precautions and calibration conditions mentioned above shall be observed. The hospital's ^{137}Cs source is then calibrated in the SSDL well type chamber using an appropriate spacer. Once the hospital source is calibrated, the hospital's well type chamber can be calibrated by following the procedures given in the previous paragraph. Once the hospital's well type chamber is calibrated, other similar standard-type sources of the hospital can be calibrated by measurements in the chamber.

2.4.2.3. Calibration of hospital's non-standard sources

The calibration of any non-standard ^{137}Cs source of the hospital, i.e. sources that are not similar to or do not fall between the characteristics of the recommended reference sources (Table II), may also be done using the calibrated well type chamber. Work at the IAEA Dosimetry Laboratory has shown that the difference in the well type chamber calibration factors for the two recommended reference sources is less than 1.0%. If a non-standard ^{137}Cs source is placed in the calibrated well type chamber, it would be expected that there might be

at most a 2% to 3% uncertainty in the calibration of the source (for reference air kerma rate). If the hospital has no well type chamber available, the calibrations should be performed by the SSDL using the SSDL's calibrated well type chamber.

Alternatively, the hospital's non-standard source can be sent to the SSDL for an in-air measurement. Using free in-air measurement technique, the reference air kerma rate of the non-standard source can be determined from the ratio of the readings with the SSDLs reference source and the source to be calibrated. Source-chamber distances need to be large enough so that the source appears to be a point source. A practical criteria is that the distance between the chamber centre and the centre of the source must be at least 10 times the length of the source in order to ensure that the error introduced due to point source approximation is less than 0.1%. Consequently, the conditions for a negligible error are generally well achieved at a source chamber distance of 1 m.

2.5. Estimation of uncertainties

The SSDL should prepare a table of uncertainties for their well type chamber calibrations similar to Table III. In addition, if in-air measurements are done, another table of uncertainties should be prepared for in-air measurements.

2.6. Traceability from hospitals to PSDL

The traceability of the reference air kerma rate of the hospital's sources is through the SSDL and the IAEA Dosimetry Laboratory to the PSDL. Prior to any calibration, either of the hospital's or the SSDLs well type chamber, a constancy test should be carried out before the transport of the well type ionization chamber.

3. CALIBRATION OF BRACHYTHERAPY SOURCES BY CAVITY IONIZATION CHAMBERS

3.1. General

In the previous section, the traceability and calibration of ^{137}Cs LDR sources have been discussed. In the present section, emphasis is given to calibration of ^{192}Ir LDR and HDR sources, although the method can be used in calibration of other brachytherapy sources as well.

In contrast to ^{137}Cs LDR calibrations, no PSDL have standards for ^{192}Ir HDR sources, and only few exists for ^{192}Ir LDR sources (e.g. NIST in the USA and NPL in the UK). The method for calibrating ^{192}Ir brachytherapy sources is therefore different from that described in the previous section.

3.2. Formalism for reference air kerma rate

The reference air kerma rate is a quantity specified at the distance of 1 m. The direct measurement at 1 m, however, is not always practical due to low signals and the possible high leakage currents of the ionization chambers used. The reference air kerma rate, K_R, may be determined from measurements made free in-air using the equation:

$$K_R = N_K \cdot (M_u / t) \cdot k_{air} \cdot k_{scatt} \cdot k_n \cdot (d/d_{ref})^2 \qquad (2)$$

where

— N_K is the air kerma calibration factor of the ionization chamber at the actual photon energy;

— M_u is the measured charge collected during the time t and corrected for ambient temperature and pressure, recombination losses and transit effects during source transfer in case of afterloading systems;

— k_{air} is the correction for attenuation in air of the primary photons between the source and the chamber;

— k_{scatt} is the correction for scattered radiation from the walls, floor, measurement set-up, air, etc.;

— k_n is the non-uniformity correction;

— d is the measurement distance i.e. the distance between the centre of the source and the centre of the ionization chamber;

— d_{ref} is the reference distance of 1 m.

It should be noted that the equation above yields the reference air kerma rate at the day of measurement. If the reference air kerma rate at an other day is required, an additional correction for the source decay is necessary.

3.3. Ionization chambers to be used

For HDR sources, ionization chambers with volumes of about 1 cm^3 can be used (e.g. Baldwin-Farmer 0.6 cm^3 chamber). For LDR sources, ionization chambers of higher volumes, up to about 1000 cm^3 may be needed to obtain a sufficient signal. For very large chambers, the

uncertainty of the non-uniformity correction factor increases [8] making the use of the chamber non-feasible.

3.4. Air kerma calibration of ionization chambers

Converting the ionization chamber reading, M_u, in Equation (2), to the reference air kerma rate requires the chamber to be air kerma calibrated at the actual photon energy of the brachytherapy source. For ^{60}Co and ^{137}Cs source calibrations, the calibration is done in external photon beams at these qualities.

The calibration of the ionization chamber for ^{192}Ir is less straight forward because none of the PSDLs have established calibration standards for the use of thimble ionization chambers for ^{192}Ir HDR and only few have standards for ^{192}Ir LDR sources. The average energy of an ^{192}Ir brachytherapy source falls in an energy gap between the standards which have been established at primary laboratories. It is therefore necessary to obtain the air kerma calibration factor for the ionization chamber using an indirect method. The following method for determination of these factors is based on the technique developed by Goetsch et al. [9]. The method was originally developed for calibration of ionization chambers for subsequent use in ^{192}Ir HDR dosimetry, but can also be used in ^{192}Ir LDR source calibrations.

The principle for air kerma calibration of the ionization chamber for ^{192}Ir is to calibrate it at an appropriate X ray quality and at ^{137}Cs, or in ^{60}Co if a ^{137}Cs beam is not available. With the knowledge of the air kerma calibration factors at these two energies, the air kerma calibration factor for ^{192}Ir is obtained by interpolation. This method requires the total wall thickness to be the same at each quality that the chamber is calibrated at [9].

The air kerma weighted average energy of an ^{192}Ir brachytherapy source is 397 keV [10, 11]. A typical X ray beam that can be used for calibration at the SSDLs is 250 kV, added filtration of 1.0 mm Al and 1.65 mm Cu, and a HVL of 2.50 mm Cu. This beam has an effective energy of 131 keV. Beams similar to this should be used for the lower energy portion of the determination of the air kerma calibration factor. Primary laboratories provide air-kerma calibration factors for these beam qualities and secondary standard chambers can be calibrated at these energies. In this report, the X ray beam referred to is the 250 kV beam above.

3.4.1. ^{137}Cs calibration point

The ionization chamber wall must be thick enough to block all electrons emanating from the source or capsule, and to provide charged particle equilibrium for the highest energy secondary electrons present in the ^{137}Cs beam. The required total wall thickness (inner wall and cap) needed is 0.36 g/cm^2 .

Air kerma calibration factors, N_K, for both the ^{137}Cs and X ray beam must be determined with the build up cap in place for both beams. The measured calibration factors give the air-kerma/charge for the chamber including the attenuation of the cap. Due to the interpolation technique [9], the attenuation of the cap and scattering effects of the chamber wall must be taken into account. Thus, the factor called A-wall, A_w, is introduced. The A_w correction factor for all energies was determined applying the linear extrapolation technique to the attenuation curves measured with different cap materials and thickness' for each beam [9, 10]. The response of the chamber alone, N_{ch}, is given by:

$$N_{ch} = N_K A_w \qquad (3)$$

The calibration factor for ^{192}Ir can then be obtained by interpolation between the N_{ch} factors for the two bracketing energies from the following equation:

$$A_{w,Ir}N_{K,Ir} = [A_{w,250kV}N_{K,250kV} + A_{w,Cs}N_{K,Cs}]/2 \quad (4)$$

where $N_{K,Ir}$, $N_{K,250kV}$ and $N_{K,Cs}$ are the air kerma calibration factors for ^{192}Ir, 250 kV X rays and ^{137}Cs qualities, respectively, and $A_{w,Ir}$, $A_{w,250kV}$ and $A_{w,Cs}$ are the corresponding A-wall factors. If $N_{K,250kV}$ and $N_{K,Cs}$ do not differ by more than 10%, which usually is the case, then the equation for $N_{K,Ir}$ can be written as [9]:

$$N_{K,Ir} = (1 + x)[N_{K,250kV} + N_{K,Cs}]/2 \quad (5)$$

where $x = 0.037 \cdot (t/9.3 \cdot 10^{22})$ for a wall thickness of t electrons/cm^2.

If a total wall thickness of $0.36 g/cm^2$ is not available, a ^{60}Co build up cap can be used instead. The difference in the $N_{K,Ir}$ calibration factor using these two different wall thickness is about 0.5%.

3.4.2. ^{60}Co calibration point

In the event that there is no ^{137}Cs beam energy at the SSDL, a ^{60}Co beam may be used as the high energy point using the appropriate build up cap and wall thickness for ^{60}Co, $0.55 g/cm^2$. This thickness must be used also in the calibration in the 250 kV X ray beam. The method for determination of the $N_{K,Ir}$ calibration factor is similar to that described above except that the relative weighting of the air kerma calibration factors is different.

The weighted interpolation factors are given by the following equations:

$$f_{w,250kV} = \left|\frac{\overline{h\upsilon}_{Ir} - \overline{h\upsilon}_{Co}}{\overline{h\upsilon}_{Co} - \overline{h\upsilon}_{250kV}}\right| = 0.8 \text{ and } f_{w,Co} = \left|\frac{\overline{h\upsilon}_{Ir} - \overline{h\upsilon}_{250kV}}{\overline{h\upsilon}_{Co} - \overline{h\upsilon}_{250kV}}\right| = 0.2 \quad (6)$$

where $\overline{h\upsilon}_{Ir}$ and $\overline{h\upsilon}_{Co}$ are the air kerma weighted average energies of ^{192}Ir gamma rays and ^{60}Co gamma rays, respectively, and $\overline{h\upsilon}_{250kV}$ represents the effective energy of the 250kV X ray beam. This results in the following equation for $N_{K,Ir}$ with the weighted air kerma values [12]:

$$N_{K,Ir} = \left(0.8 \cdot A_{w,250kV}N_{K,250kV} + 0.2 \cdot A_{w,Co}N_{K,Co}\right)/A_{w,Ir} \quad (7)$$

Table IV includes A_w factors for different ionization chambers. If the chamber in use is not listed in the table, then A_w can be set to 1.000 for each energy in Equation (7), and the calibration factor is determined with

$$N_{K,Ir} = 0.8 \cdot N_{K,250kV} + 0.2 \cdot N_{K,Co} \quad (8)$$

With the use of Equation (8) the uncertainty in the air kerma calibration factor for ^{192}Ir increases by approximately 0.5%.

TABLE IV. MONTE-CARLO CALCULATED A_W FACTORS FOR DIFFERENT IONIZATION CHAMBERS FOR 250 kV X ray, ^{192}Ir AND ^{60}Co. THE UNCERTAINTIES (ONE STANDARD DEVIATION) ARE < 0.1%. VALUES FROM [13]

Ionization chamber	Air cavity length/ radius (mm)	Wall material/ thickness gcm^{-2}	Build-up cap material/ thickness gcm^{-2}	A_w 250kV	A_w ^{192}Ir	A_w ^{60}Co
Capintec 0.07 cm^3 PR-05P mini	5.5 / 2.0	C552 / 0.220	Polyst./ 0.598	0.986	0.980	0.989
Capintec 0.14 cm^3 PR-05 mini	11.5 / 2.0	C552 / 0.220	Polyst./0.598	0.988	0.983	0.989
Capintec 0.65 cm^3 PR-06C Farmer	22.3 / 3.2	C552 / 0.050	C552 / 0.924	0.998	0.980	0.984
Capintec 0.65 cm^3 PR-06C Farmer	22.3 / 3.2	C552 / 0.050	Polyst. / 0.537	0.997	0.986	0.990
Capintec 0.65 cm^3 PR-06C Farmer	22.3 / 3.2	C552 / 0.050	PMMA / 0.547	0.992	0.984	0.989
Capintec 0.6 cm^3 PR-05P AAPM	23.8 / 3.3	Graphite / 0.046	PMMA / 0.625	0.995	0.986	0.986
Exradin 0.003 cm^3 A14 (2mm cap)	4.0 / 2	C552 / 0.176	C 552 / 0.352	1.000	0.993	0.993
Exradin 0.003 cm^3 T14 (4mm cap)	4.0 / 2	A150 / 0.113	A150 / 0.455	0.993	0.991	0.980
Exradin 0.05 cm^3 A1 (2mm cap)	5.7 / 2	C552 / 0.176	C 552 / 0.352	0.987	0.988	0.990
Exradin 0.05 cm^3 A1 (4mm ap)	5.7 / 2	C552 / 0.176	C 552 / 0.712	0.997	0.977	0.982
Exradin 0.05 cm^3 T1 (4mm cap)	5.7 / 2	A150 / 0.113	A150 / 0.455	0.985	0.988	0.990
Exradin 0.5 cm^3 A2 (2mm cap)	11.4 / 4.8	C552 / 0.176	C 552 / 0.352	0.986	0.978	0.984
Exradin 0.5 cm^3 A2 (4mm cap)	11.4 / 4.8	C552 / 0.176	C 552 / 0.712	0.989	0.973	0.976
Exradin 0.5 cm^3 P2 (4mm cap)	11.4 / 4.8	Polyst./0.105	Polyst. / 0.420	0.986	0.982	0.988
Exradin 0.5 cm^3 T2 (4mm cap)	11.4 / 4.8	A150 / 0.113	A150 / 0.455	0.983	0.979	0.985
Exradin 0.65 cm^3 Farmer A 12	24.2 / 3.1	C552 / 0.088	C 552 / 0.493	0.999	0.988	0.991
Far West tech 0.1 cm^3 IC-18	9.5 / 2.3	A150 / 0.183	A150 / 0.386	0.993	0.983	0.990
FZK 0.4 cm^3 TK 01 waterproof	12 / 3.5	Delrin / 0.071	Delrin / 0.430	0.988	0.982	0.989
NE 0.2 cm^3 Farmer 2515	7 / 3.0	Tufnol / 0.074	PMMA / 0.543	0.993	0.980	0.987
NE 0.2 cm^3 Farmer 2515/3	7 / 3.2	Graphite / 0.066	PMMA / 0.543	0.994	0.982	0.986
NE 0.2 cm^3 Farmer 2577	8.3 / 3.2	Graphite / 0.066	Delrin / 0.552	0.988	0.981	0.986
NE 0.6 cm^3 Farmer 2505	24 / 3.0	Tufnol / 0.075	PMMA / 0.545	0.997	0.989	0.990
NE 0.6 cm^3 Farmer 2505/A	24 / 3.0	Nylon 66 / 0.063	PMMA / 0.545	0.996	0.984	0.989
NE 0.6 cm^3 Farmer 2505/3A	24 / 3.2	Graphite / 0.065	PMMA / 0.551	0.998	0.989	0.989
NE 0.6 cm^3 Farmer 2505/3B	24 / 3.2	Nylon 66/0.041	PMMA / 0.551	0.995	0.990	0.989
NE 0.6 cm^3 Farmer 2571	24.1 / 3.15	Graphite / 0.065	Delrin / 0.551	0.999	0.989	0.988
NE 0.6 cm^3 Farmer 2571	24.1 / 3.15	Graphite / 0.065	PMMA / 0.550	0.998	0.989	0.989
NE 0.6 cm^3 Farmer 2581	24.1 / 3.2	A150 / 0.040	PMMA / 0.584	0.986	0.988	0.987
NE 0.6 cm^3 Farmer 2581	24.1 / 3.2	A150 / 0.041	Polyst. / 0.584	0.991	0.990	0.991
NE 0.325 cm^3 2561	9.2 / 3.7	Graphite / 0.09	Delrin / 0.600	0.987	0.984	0.984
PTW 0.1 cm^3 23 323 micro	12 / 1.75	PMMA / 0.208	PMMA / 0.357	0.999	0.991	0.991
PTW 1.0 cm^3 23 331 rigid	22 / 3.95	PMMA / 0.060	PMMA / 0.345	0.997	0.992	0.993
PTW 0.3 cm^3 23 332 rigid	18 / 2.5	PMMA / 0.054	PMMA / 0.357	1.000	0.993	0.994
PTW 0.6 cm^3 Farmer 30 001	23 / 3.05	PMMA / 0.045	PMMA / 0.541	0.997	0.990	0.990
PTW 0.6 cm^3 Farmer 30 002	23 / 3.05	Graphite / 0.079	PMMA / 0.541	0.993	0.989	0.989
PTW 0.6 cm^3 Farmer 30 004	23 / 3.05	Graphite / 0.079	PMMA / 0.541	0.997	0.990	0.990
PTW 0.125 cm^3 31 002 flexible	6.5 / 2.75	PMMA / 0.079	PMMA / 0.357	0.990	0.992	0.992

TABLE IV (cont.)

Ionization Chamber	Air cavity length /radius (mm)	Wall material/ thickness gcm^{-2}	Build-up cap material/ thickness gcm^{-2}	A_w 250kV	A_w ^{192}Ir	A_w ^{60}Co
PTW 0.3 cm^3 31 003 flexible	16.3 / 2.75	PMMA / 0.079	PMMA / 0.357	1.000	0.993	0.993
Victoreen 0.3 cm^3 Radocon III 550	23 / 2.4	Polyst./ 0.117	PMMA / 0.481	0.997	0.991	0.991
Victoreen 0.3 cm^3 30-348	18 / 2.5	PMMA / 0.06	PMMA / 0.360	0.994	0.993	0.994
Victoreen 0.6 cm^3 30-351	23 / 3.1	PMMA / 0.06	PMMA / 0.360	0.995	0.993	0.994
Victoreen 1.0 cm^3 30-349	22 / 4.0	PMMA / 0.06	PMMA / 0.360	0.996	0.992	0.992
Victoreen 0.4 cm^3 30-361	22.3 / 2.4	PMMA / 0.144	PMMA / 0.360	1.000	0.992	0.992
SSI Graphite	17.9 / 4.0	Graphite / 0.084	Graphite / 0.384	0.990	0.990	0.990
SSI A150	17.9 / 4.0	A150 / 0.056	A150 / 0.373	0.993	0.991	0.991
Wellhöfer 0.03 cm^3 IC-04	3.6 / 2.0	C552 / 0.068	PMMA / 0.354	0.996	0.991	0.991
Wellhöfer 0.08 cm^3 IC-06	4 / 3.0	C552 / 0.068	PMMA / 0.354	0.995	0.990	0.990
Wellhöfer 0.13 cm^3 IC-15	5.8 / 3.0	C552 / 0.068	PMMA / 0.354	0.993	0.990	0.990
Wellhöfer 0.3 cm^3 Farmer IC 28	9 / 3.1	C552 / 0.070	POM / 0.560	0.993	0.988	0.988
Wellhöfer 0.6 cm^3 Farmer IC 69	23 / 3.1	Delrin / 0.070	POM / 0.560	1.000	0.990	0.990
Wellhöfer 0.6 cm^3 Farmer IC 70	23 / 3.1	Graphite / 0.068	POM / 0.560	1.000	0.990	0.990

3.5. Correction factors for free in-air measurements

Calibration of brachytherapy sources by free in-air measurements are needed in order to be able to calibrate well type ionization chambers for use at the hospital level. To obtain the reference air kerma rate with a least possible uncertainty necessitates a cautious performance of the measurements and the use of up-to-date correction factors. In this section the various correction factors are discussed in detail, for reference air kerma rate determination of ^{192}Ir LDR and HDR sources and ^{137}Cs and ^{60}Co sources.

The fundamental principle involved in calibration of an HDR source free in-air follows closely that of calibrating a cobalt teletherapy unit, that is, determination of air kerma using an appropriately calibrated ionization chamber. The distance for the teletherapy measurement approximates the distance typical of patient treatment, and is large compared to the dimensions of the detector. In this well-collimated beam the uncertainty in the position of the point-like detector contributes little to the overall uncertainty.

For the uncollimated brachytherapy source measured at a short distance, the situation changes markedly. At typical brachytherapy treatment distances, ranging from a few millimetres to a few centimetres, conventional ionization chambers cannot be treated as point-like detectors. In addition, at these short distances, air kerma measurements are extremely sensitive to positional uncertainties. Therefore, the calibration requires some device (a jig) of low-density plastic to hold the chamber and the source in precise position during the calibration. Any mounting device unavoidably compromises between mechanical rigidity and minimizing scatter. While corrections for scatter can be determined, they should be minimized. Both of these issues contribute a major part to the overall calibration uncertainty.

3.5.1. Measurement distances

Increasing the distance decreases the uncertainty in the calibration distance and the effect of the finite size of the ionization chamber. However, this improvement results in a reduced signal and an increased relative importance of room and equipment scatter. There are four effects that contribute to the uncertainties in calibration of brachytherapy sources using an ionization chamber. These effects expressed as a function of distance between the source and the chamber (SCD) are:

— chamber size, which decreases with increasing SCD;
— scatter, which as a percentage of the total signal increases with increasing SCD;
— positional uncertainty, which follows the inverse square law and thus decreases with increasing SCD;
— leakage current relative to the ionization reading, the effect of which increases with increasing SCD.

The measurement distance should be selected so that the combined uncertainty due to the above effects will be minimum. This would generally be the distance where the various correction factors, when combined in quadrature, has the minimum value. For a combination of ^{192}Ir HDR source and a Farmer-type chamber, the optimum distance has been shown to be 16 cm [14]. With the possible exception of the scattered radiation, it can be noted that the different contributions listed above have only a minor energy dependence. Thus, the optimum distance for ^{60}Co and ^{137}Cs HDR source calibrations should be approximately the same as that for an ^{192}Ir HDR source. It must be pointed out that the non-uniformity correction factors used in this report are calculated assuming a point source geometry. Thus, in all free in-air measurements, in HDR as well as LDR, the distances used must be large enough so that the source can be considered as a point source. Furthermore, the inclusion of the inverse square relation in Equation (2) implies that sufficiently large distances must be used.

It is recommended in this report that measurements should be made at multiple distances and the reference air kerma rate should be determined from the measurements made at each distance. This procedure will give redundancy and large variations in the K_R, as determined from the different measurements, are indications of bad experimental conditions. For HDR source calibrations, the measurements distances can be selected around the optimum distance (e.g. between 10 cm and 40 cm).

3.5.2. The scatter correction factor

To minimize the contribution of scattered radiation, the source and chamber should be placed in the centre of the room and well above the floor (at least 1 m from any wall or floor). All measurements should preferably be carried out using the same position of the source and chamber.

Two methods have been used to determine the scatter correction: the multiple distance method [9] and the shadow shield method [8, 11, 15]. In the former method, the air kerma rate due to scattered radiation is assumed to be constant over the measurement distances.

In the shadow shield method, a cone of some high Z material is placed between the source and the chamber in order to prevent the primary photons to reach the chamber. The ratio of the measured charge with and without the shield in place can be used to calculate the scatter correction factor. The height of the cone must be large enough to provide sufficient

attenuation and should not be placed too close to the chamber due to possible scattering from the cone. Therefore, the multiple distance method is recommended for measurements which involve short distances, and in particular in ^{137}Cs and ^{60}Co HDR source calibrations.

In the multiple distance method, readings are made at a series of distances with carefully measured separations. If a linear scanner is used, the readings are to be taken by scanning continuously in one direction through the sequential distances in order to avoid any backslash errors in the scanner mechanism. The readings made at the different distances reflect the inverse square law differences between them, and an assumedly constant amount of scatter.

It is essential in this method that the changes in distance be precise and correct, in order to derive the correction c that yields the "true" centre-to-centre source to chamber distances, d'. The distance for a reading is expressed by the following equation:

$$d' = d + c \tag{9}$$

where

— d' is the centre-to-centre source chamber distance accounting for the offset c in the distance;

— d is the apparent centre-to-centre source chamber distance;

— c is the offset in the set-up distance (c can be positive or negative).

The contribution of scatter radiation to the air kerma rate, K_s, is included in the measured air kerma rate, $K(d')$. Therefore the air kerma value due to the primary photons only, $K_p(d')$, is given by

$$K_p(d') = K(d') - K_s \tag{10}$$

Combining the Equations (9) and (10) yields:

$$K_p(d') \cdot (d')^2 = (K(d') - K_s) \cdot (d + c)^2 \tag{11}$$

for any distance. The air kerma due to the primary photons varies as the inverse of the square of the distance, and therefore, measurements at three distances can be used to determine the three unknowns, $K_p(d')$, K_s, and c. For redundancy preferably five or seven distances, e.g. in HDR brachytherapy source calibrations 10, 15, 20, 25, 30, 35 and 40 cm should be used. The seven distances redundantly determine the scatter contribution and factor c since there are 3 unknowns with 35 solutions. A computer generated solution then can be used to average the solutions. Thus, finally the scatter correction k_{scatt} can be determined as follows:

$$k_{scatt} = 1 - K_s / K(d') = 1 - K_s / (N_K \cdot M_u \cdot k_n) \tag{12}$$

where the measured charge M_u has been corrected as described earlier. The value of c should be within ± 2 mm. If there is a large variation in c when the redundant solutions are made, it is indicative of an error made in the measurement process. In such cases, the entire process should be carefully reviewed and the measurements repeated.

The shadow shield method has mainly been used to determine the scatter correction factor at 1 m distance. Table V shows the results of a few experimental determinations of the scatter correction using the shadow shield method. The results suggest that the room size may not be critical for this factor.

TABLE V. SCATTER CORRECTION FACTORS DETERMINED WITH THE SHADOW SHIELD METHOD AT 1 m DISTANCE FROM AN ^{192}Ir SOURCE

Author		k_{scatt}	Chambers	Room size m × m × m
Verhaegen et al.	[8]	0.940	NE 2551 and Exradin A6	4 × 4 × 4
Verhaegen et al.	[8]	0.975	PTW LS-10	4 × 4 × 4
Petersen et al.	[16]	0.940	Exradin A5	6 × 6 × 3
Drugge	[11]	0.940	Exradin A5 and NE 2530/1	3.5 × 5 × 3.5
Piermattei et al.	[15]	0.928	Exradin A4	–
Piermattei et al.	[15]	0.941	Exradin A6	–

In ^{192}Ir dosimetry it has been shown that the scatter correction factors obtained with the two methods are in a good agreement [8, 11].

3.5.3. The non-uniformity correction factor

In the measurements of brachytherapy sources free in-air, the non-collimated geometry, with high divergence of the incident photons, differs from the geometry of the collimated photon beams such as those external beams used for calibrating the chamber. There will be a marked variation in the photon fluence over the different parts of the chamber.

The electrons entering the air cavity are mainly generated in the inner wall of the chamber. Due to the non-uniform photon fluence over the wall, the generation of electrons from the wall varies significantly from place to place in the wall. The net result of this is a non-uniform electron fluence in the air cavity of the chamber.

In order to take into account this non-uniformity, to convert the measured charge or current into air kerma rate at the measurement distance, it is necessary to apply a non-uniformity correction factor, k_n. This factor depends on the

— shape and dimensions of the ionization chamber (spherical, cylindrical, internal radius and length);
— measurement distance and the source geometry ('point source', line source, etc.);
— material in the inner wall of the chamber [17];
— energy of the photons emitted from the source [17].

The most widely used non-uniformity correction factors are those given by Kondo and Randolph [18]. In their theory, the electron fluence in the air cavity of the ionization chamber is assumed to be isotropic. The theory was later extended by Bielajew [17] who included a more realistic angular distribution of electron fluence in the air cavity of the chamber. In contrast to the isotropic theory, this anisotropic theory predicts the wall material and a photon energy dependence in the non-uniformity correction factor. The relationship between the two theories is given by

$$A_{pn}(d) = A_{pn}^{KR}(d) + \omega A'_{pn}(d) \qquad (13)$$

where $1/A_{pn}^{KR}(d)$ is the non-uniformity correction factor obtained from the isotropic theory of Kondo and Randolph and $1/A_{pn}(d)$ is the non-uniformity correction factor according to the anisotropic theory of Bielajew. $A_{pn}(d)$ takes into account the anisotropic electron fluence within the air cavity and the degree of anisotropy is given by the energy and material dependent factor ω. Thus, the theory by Bielajew predicts an energy and inner wall material

dependence in the non-uniformity correction factor. In contrast, the theory by Kondo and Randolph is independent of both these factors.

It is recommended in this report that the factor $1/A_{pn}(d)$ according to the theory by Bielajew be used for determination of k_n. Thus,

$$k_n = 1/A_{pn}(d) \tag{14}$$

For cylindrical ionization chambers, it has been shown that the non-uniformity correction factor obtained with the anisotropic theory is, for commonly used chamber wall materials, quite insensitive to the ω-values [19]. Table VI gives values of ω for some commonly used inner wall materials. For materials that are not included in the table, a good approximation is to use the value for that material with similar dosimetric properties as that listed in Table VI. For example, the ω value for C552 can be taken to be the same as that for graphite, i.e. 0.992. It should be noted that the wall material referred to is the material in the inner wall of the ionization chamber, not the material in the build up cap.

TABLE VI. MATERIAL- AND PHOTON ENERGY DEPENDENT FACTORS, ω

Inner wall material	ω
A-150	1.066
PMMA	1.014
Graphite	0.992

The values in Table VI were calculated for an unfiltered ^{192}Ir source. As shown for graphite (the inner wall material of an NE2571 chamber) in Fig. 7, the non-uniformity correction factor has only a minor energy dependence. Other wall materials listed in Table VI show similar behaviour. Without loss of accuracy, these values can therefore be used in ^{137}Cs and ^{60}Co calibrations.

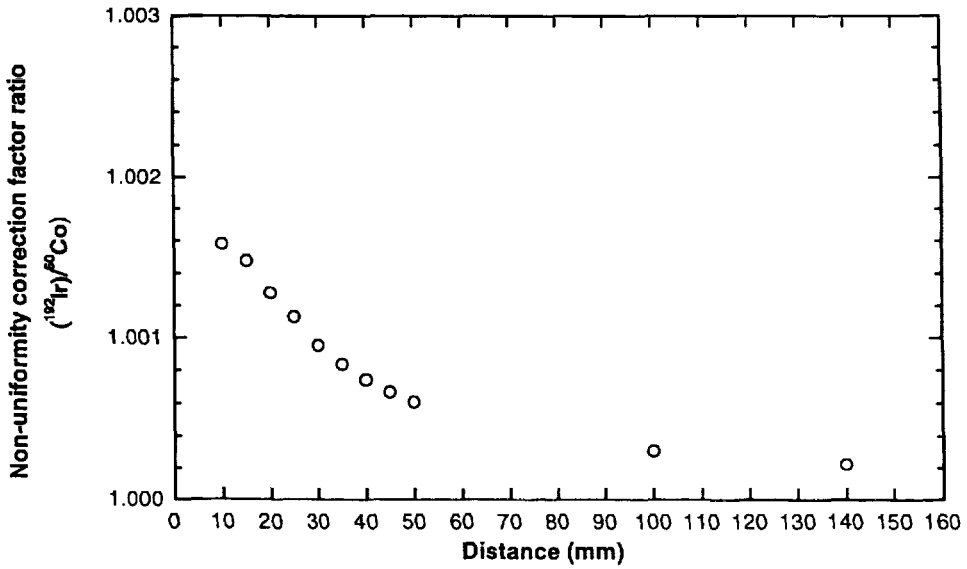

Figure 7. Ratio of non-uniformity correction factor for an NE2571 ionization chamber at ^{192}Ir *and* ^{60}Co *qualities.*

The parameters, $A_{pn}^{KR}(d)$ and $A_{pn}^{'}(d)$, for the calculation of the non-uniformity correction factor for cylindrical chambers are given in Tables VII and VIII. These are given as a function of the cylindrical chamber's shape factor, $\sigma = R_C/L_C$, and the distance factor, $\alpha = R_C/d$. In these formulas, R_C is the chamber's internal radius, L_C is the internal half-length of the chamber and d is the measurement distance.

TABLE VII. VALUES OF FACTORS $A_{pn}^{KR}(d)$ FOR CYLINDRICAL IONIZATION CHAMBERS. R_C AND L_C ARE THE CHAMBERS' INTERNAL RADIUS AND HALF-LENGTH

Distance factor $\alpha = R_c/d$	Shape factor $\sigma = R_c/L_c$								
	0 05	0 10	0 25	0 50	0 70	0 80	1 00	2 00	4 00
0 000	1 0000	1 0000	1 0000	1 0000	1 0000	1 0000	1 0000	1 0000	1 0000
0 005	0 9967	0 9992	0 9999	1 0000	1 0000	1 0000	1 0000	1 0000	1 0000
0 010	0 9869	0 9967	0 9995	0 9999	1 0000	1 0000	1 0000	1 0001	1 0001
0 050	0 7854	0 9273	0 9878	0 9980	0 9998	1 0003	1 0008	1 0015	1 0015
0 100	0 5546	0 7863	0 9541	0 9921	0 9992	1 0010	1 0031	1 0059	1 0061
0 200	0 3349	0 5586	0 8524	0 9694	0 9963	1 0035	1 0123	1 0238	1 0250
0 300	0 2401	0 4263	0 7476	0 9359	0 9908	1 0067	1 0268	1 0551	1 0586
0 400	0 1892	0 3468	0 6615	0 8980	0 9831	1 0099	1 0460	1 1019	1 1103
0 500	0 1584	0.2960	0 5966	0 8629	0 9755	1 0142	1 0698	1 1676	1 1864
0 600	0 1388	0 2628	0 5508	0 8370	0 9732	1 0235	1 1002	1 2576	1 2985
0 700	0 1266	0 2421	0 5226	0 8263	0 9842	1 0457	1 1443	1 3809	1 4681
0 800	0 1206	0 2326	0 5146	0 8416	1 0233	1 0971	1 2200	1 5592	1 7406
0 900	0 1235	0 2398	0 5429	0 9166	1 1364	1 2284	1 3864	1 8736	2 2432

TABLE VIII. VALUES OF FACTORS $A_{pn}^{'}(d)$ FOR CYLINDRICAL IONIZATION CHAMBERS. R_C AND L_C ARE THE CHAMBERS' INTERNAL RADIUS AND HALF-LENGTH

Distance factor $\alpha = R_c/d$	Shape factor $\sigma = R_c/L_c$								
	0 05	0 10	0 25	0 50	0 70	0 80	1 00	2 00	4 00
0 000	0 0000	0 0000	0 0000	0 0000	0 0000	0 0000	0 0000	0 0000	0 0000
0 005	-0 0014	-0 0012	-0 0009	-0 0005	-0 0003	-0 0002	-0 0001	0 0002	0 0004
0 010	-0 0027	-0 0024	-0 0017	-0 0009	-0 0005	-0 0004	-0 0001	0 0005	0 0007
0 050	-0 0056	-0 0093	-0 0083	-0 0047	-0 0027	-0 0019	-0 0007	0 0024	0 0036
0 100	-0 0032	-0 0103	-0 0148	-0 0093	-0 0055	-0 0039	-0 0014	0 0047	0 0072
0 200	-0 0011	-0 0062	-0 0203	-0 0179	-0 0115	-0 0086	-0 0036	0 0093	0 0147
0 300	-0 0006	-0 0036	-0 0190	-0 0242	-0 0180	-0 0143	-0 0071	0 0136	0 0229
0 400	-0 0003	-0 0023	-0 0159	-0 0274	-0 0241	-0 0205	-0 0122	0 0173	0 0323
0 500	-0 0002	-0 0016	-0 0130	-0 0279	-0 0285	-0 0261	-0 0186	0 0194	0 0433
0 600	-0 0002	-0 0012	-0 0106	-0 0267	-0 0309	-0 0302	-0 0250	0 0188	0 0563
0 700	-0 0001	-0 0009	-0 0088	-0 0247	-0 0314	-0 0324	-0 0303	0 0138	0 0712
0 800	-0 0001	-0 0007	-0 0073	-0 0224	-0 0306	-0 0328	-0 0338	0 0036	0 0851
0 900	-0 0001	-0 0006	-0 0062	-0 0202	-0 0290	-0 0321	-0 0354	-0 0100	0 0869

The anisotropic non-uniformity correction factors for Farmer-type chambers (internal length 24.1 mm, internal radius 3.15 mm, e.g. NE2571, NE2581) at different distance from ^{60}Co, ^{137}Cs and ^{192}Ir brachytherapy sources are given in Table IX [20]. For the calculation of the factors in Table IX, the cone (the deviation from cylinder geometry) at the tip of the chamber has been taken into consideration, resulting in values which are slightly different from those that could be derived from Tables VII and VIII.

For spherical ionization chambers, $\omega = 0$, and the non-uniformity correction factors given by Kondo and Randolph can be directly applied. The $A_{pn}(d)$ factors for spherical chambers are reproduced in Table X.

TABLE IX. NON-UNIFORMITY CORRECTION FACTORS FOR FARMER-TYPE IONIZATION CHAMBERS (INTERNAL RADIUS 3.15 mm, LENGTH 24.1 mm)

Distance (mm)	k_n
100	1.009
150	1.005
200	1.004
250	1.003
300	1.002
400	1.002
500	1.001

TABLE X. $A_{pn}(d)$ FACTORS FOR SPHERICAL IONIZATION CHAMBERS

	Chamber radius (cm)									
Distance (cm)	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
10.0	1.014	1.022	1.032	1.044	-	-	-	-	-	-
15.0	1.006	1.009	1.014	1.019	1.025	1.032	1.040	1.049	-	-
20.0	1.003	1.005	1.008	1.010	1.014	1.017	1.022	1.026	1.032	1.038
25.0	1.002	1.003	1.005	1.007	1.009	1.011	1.014	1.017	1.020	1.023
30.0	1.001	1.002	1.003	1.005	1.006	1.008	1.009	1.011	1.014	1.016
35.0	1.001	1.002	1.002	1.003	1.004	1.006	1.007	1.008	1.010	1.012
40.0	1.001	1.001	1.002	1.003	1.003	1.004	1.005	1.006	1.008	1.009
45.0	1.001	1.001	1.001	1.002	1.003	1.003	1.004	1.005	1.006	1.007
50.0	1.001	1.001	1.001	1.002	1.002	1.003	1.003	1.004	1.005	1.006
60.0	1.000	1.001	1.001	1.001	1.001	1.002	1.002	1.003	1.003	1.004
70.0	1.000	1.000	1.001	1.001	1.001	1.001	1.002	1.002	1.002	1.003
80.0	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.002	1.002	1.002
90.0	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.002
100.0	1.000	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.001	1.001

3.5.4. Correction for the attenuation of primary photons in air

For determination of the reference air kerma rate from the measured air kerma at the distance d, it is necessary to correct for the attenuation of the primary photons between the source and the ionization chamber. Table XI gives the k_{air} correction factors at different distances between the source and the ionization chamber [8, 11, 21].

TABLE XI. CORRECTION FACTORS FOR AIR ATTENUATION OF THE PRIMARY PHOTONS FROM ^{192}Ir, ^{137}Cs AND ^{60}Co BRACHYTHERAPY SOURCES

Distance (cm)	^{192}Ir	^{137}Cs	^{60}Co
10	1.001	1.000	1.000
20	1.002	1.000	1.000
30	1.004	1.001	1.000
40	1.005	1.001	1.000
50	1.006	1.001	1.000
60	1.007	1.001	1.000
70	1.009	1.002	1.000
80	1.010	1.002	1.000
90	1.011	1.002	1.000
100	1.012	1.002	1.000

3.5.5. Correction for transit effects, leakage current and recombination losses

While the source moves into the measurement position, and then away after the measurement, the detector measures a signal, referred to as the transit signal. This transit signal acts the same as the end effect of a cobalt teletherapy unit. The magnitude strongly depends on the source-to-detector distance, and is significant at calibration distances. Several techniques can be used to eliminate the transit component of the signal:

— Using an externally-triggered electrometer to collect charge during an interval after the source has stopped moving [9].
— Subtracting two readings taken for differing intervals to eliminate the transit charge common to both.
— Using a current reading after the source has stopped moving (if the signal is large enough).

The importance of electrical leakage currents in the individual dosimetry system should be evaluated since the signal levels are typically 50 to 100 times less than usually encountered in teletherapy measurements. This can be significant for most thimble or Farmer type ionization chambers. Larger volume spherical ionization chambers do not have this effect to a great extent. Generally if the leakage is of the order of 0.1% of the signal, it should be accounted for.

A correction is also needed for the recombination losses and for the ambient temperature and pressure [6].

4. CALIBRATION OF BRACHYTHERAPY SOURCES WITH WELL TYPE IONIZATION CHAMBERS

4.1. Calibration of well type chambers

To establish a traceability for brachytherapy source calibrations, from the PSDL through the SSDL to the users at the hospital level, the combined use of reference sources and well type ionization chambers is recommended. In this methodology, the traceability link from the user to the SSDL is established through the calibration of hospital's well type ionization chambers with the help of reference sources and well type ionization chambers maintained by the SSDL. An extension of this principle via free in-air measurements may be used for ^{192}Ir, ^{137}Cs and ^{60}Co HDR sources. ^{125}I sources are a special consideration.

Since the PSDLs so far do not provide calibrations directly for ^{192}Ir HDR sources, the calibration of these sources require free in-air measurements as described in the Section 3, with subsequent calibration of well type ionization chambers with the calibrated sources. For calibrations of ^{125}I, SSDLs should acquire a calibration which then can be transferred to the hospital. Due to the short half-life of the ^{192}Ir and ^{125}I sources, the constancy of the calibration factor of the well type ionization chamber for these sources shall be tested by a suitable long-lived source e.g. ^{137}Cs LDR source.

In all calibrations of well type chambers, the chamber's calibration point is with the source at the position of maximum response. This position is dependent on the source type (cf. Fig. 3) and must be determined prior to the calibration.

4.1.1. Calibration for HDR sources

With the knowledge of the reference air kerma rate of the HDR brachytherapy source, the well type chamber's calibration factor is determined using the formalism given in Equation (1). The source is positioned at the maximum response.

4.1.2. Calibration for ^{192}Ir LDR wires

LDR sources of ^{192}Ir are supplied in different forms, e.g. wires, hairpins, single pins, etc. The wire has a total length of 500 mm and is delivered in a form of a coil. It is not recommended to calibrate the whole coil by free in-air measurements due to the complicated geometry and possible self absorption of photons in the coil. The procedure for ^{192}Ir LDR wires is as follows:

— A piece with a length of 10 mm of the ^{192}Ir wire is calibrated free in-air using the methods described in Section 3.
— The calibrated wire is used to calibrate a well type chamber. This calibration is done with the source centre at the position of maximum response of the well type chamber.

With this method, the well type chamber is calibrated in terms of reference air kerma rate for the specific length of 10 mm of the ^{192}Ir wire. Thus, a calibration factor, $N_{K_R,10mm}$, can be determined.

4.1.3. Calibration for ^{125}I seeds

For ^{125}I LDR brachytherapy sources, the SSDL should obtain a calibration of an ^{125}I seed from a primary laboratory. This is the preferable method. Since the half life of ^{125}I is so short, the time for this process is critical so that the SSDL does not receive a source that is of such

low activity that the well type ionization chamber cannot be calibrated with the acceptable uncertainty. The SSDL should encourage the PSDL to give the calibration of the ^{125}I source and provide the shipping in the shortest possible time period. Upon receipt of the seed, a ratio of the calibration factors between the ^{125}I seed and another long lived source, such as ^{137}Cs, should be done. If this short turnaround by the PSDL cannot be done, the well type chamber of the SSDL may be calibrated by another SSDL (e.g. the University of Wisconsin in the USA), for both ^{125}I and for ^{137}Cs. The ratio of the ^{125}I source calibration factor to that of the ^{137}Cs source can be provided. Once this ratio is determined, it can be expected to remain constant within 0.8% for air communicating well type chambers [22]. When the SSDL receives their well type chamber, a measurement of their calibrated ^{137}Cs source should be made. Thus, constancy testing would maintain the metrological quality of the source calibrations of the well type chamber. The SSDL should continuously monitor the long lived source calibration point on their well type chamber. This value should remain within 1%. If this value changes by more than 1%, a re-calibration procedure for the well type ionization chamber should be instituted.

4.2. Calibration of brachytherapy sources with well type chambers

4.2.1. Calibration of HDR sources

The reference air kerma rate of the HDR brachytherapy source is determined from

$$K_R = N_{K_R} \cdot (M_u / t) \tag{15}$$

where N_{K_R} is the reference air kerma rate calibration factor for the well type chamber, M_u is the charge corrected for ambient temperature and pressure in case of an open chamber, recombination losses and in the case of afterloading units, for the transient effect if the electrometer is used in charge mode and t is the measurement time.

A minimum of five measurements are taken. These measurements should be within 0.3% of the average reading. The average of two sets of readings should be within 0.5%. This average value may be used to determine K_R using Equation (15).

4.2.2. Calibration of multiple LDR/MDR ^{137}Cs sources

Nucletron LDR/MDR Selectron remote afterloading machines use 20 to 48 spherical ^{137}Cs sources that are of similar activity and, which after loading into the machine cannot be specifically identified. These sources should be calibrated with a well type chamber before loaded into the machine to obtain the range and distribution of the reference air kerma rates. The variation in a batch should be within $\pm 3.5\%$.

4.2.3. Calibration of ^{192}Ir LDR wires

^{192}Ir LDR sources are available in the form of lengths cut from a coil of wire, single pins and hairpins. It is necessary for individual wire sources to be assayed before clinical use with a calibrated well type chamber. The SSDL should provide a calibration factor for the well type chamber for a 10 mm length of wire and for other types of individual sources.

Ideally, the ratio $M_u / (L \cdot K_{R,wire})$, where $K_{R,wire}$ is the reference air kerma rate per unit source length, should be independent of the wire length L. As can be seen from Fig. 8, this

ratio will vary with the source length and for calibration of wires of different lengths, it is necessary to apply a correction factor, k_L, which will depend upon the source length L. The reference air kerma rate of the wire with a length L is then:

$$K_R = N_{K_R,10mm} \cdot M_u \cdot k_L \quad (16)$$

where $N_{K_R,10mm}$ is the reference air kerma rate calibration factor for a 10 mm length ^{192}Ir wire, M_u the corrected charge and k_L is the correction factor that takes into account the differences in the length of the source that is calibrated and the 10 mm wire that was used to calibrate the well type chamber.

The factor k_L may be determined with a 10 mm piece of wire which is used to measure the chamber response for different positions of the wire along the central axis of the chamber [11]. From these measurements it is possible to construct a curve similar to that shown in Fig. 8 and the correction factor can be calculated for different lengths of wires.

In Table XII correction factors are given for the HDR 1000 (Standard Imaging) chamber and the Nucletron SDS (PTW) well type chambers.

TABLE XII. CORRECTION FACTORS, k_L, FOR DIFFERENT LENGTHS OF LDR ^{192}Ir WIRES

Wire length (mm)	HDR 1000	SDS
10	1.000	1.000
30	1.005	1.012
50	1.012	1.017
70	1.029	1.038
90	1.050	1.070

The values in Table XII are consistent with values found by Drugge [11]. To use these values, the centre of the wire must be positioned at the calibration point of the well type chamber, i.e., at the position of maximum response. Positioning of hairpin and single pin sources in calibration procedures must replicate the procedure used at the SSDL. Some well type chambers have a small diameter cavity and are sensitive to radial positional changes. The National Physical Laboratory (UK) provide calibration factors for use with the NPL isotope calibrator reference chamber [23, 24].

5. QUALITY CONTROL

5.1. Safety aspects in the use of brachytherapy sources

The dose delivered to a patient undergoing brachytherapy treatment is directly proportional to the source strength. At the delivery of brachytherapy sources, these are accompanied with a certificate stating the source strength as determined by the manufacturer. Based on QC protocols, modern practice strongly recommends not to use this value as an input to dose calculation without independent verification by a qualified medical physicist.

A number of accidents have been reported in LDR and HDR brachytherapy treatments [25, 26], resulting in an incorrect dose to the patient. The type of accident and their frequency is summarised in Table XIII.

Errors in the specification of the source activity, dose calculation or in the quantities and units resulted in doses that were between 20% and 170% of the prescribed dose. Some of the accidents were caused by human mistakes, e.g. incorrect source was used for treatments because the colour coding of the source had faded. This is given under "Other" in the table, which includes also accidents caused by badly implanted sources, removal of the sources by the patient or otherwise dislodged sources. The most severe accident reported was due to equipment failure, where a lethal dose was delivered to the patient.

Of the total 32 cases reported, 7 could be attributed to the use of sources with incorrectly determined or stated activity. In 6 of these, no independent check of the source strength was done. In 2 other cases the accident was caused by a mistake due to the incorrect use of quantities and units.

TABLE XIII. TYPE AND FREQUENCY FOR ACCIDENTS REPORTED IN BRACHYTHERAPY TREATMENTS

Accident caused by	Number of cases
Dose calculation error	6
Error in quantities and units	2
Incorrect source strength	7
Equipment failure	4
Other	13
Total	32

The recommended quantity by the ICRU for the specification of brachytherapy sources is reference air kerma rate [2, 3]. However, other quantities are still in wide use, often dictated by those used in dose planning systems. In such cases the use of conversion factors is necessary. Since conversion factors can vary substantially, due to the basic data or type of attenuation included, it is strongly suggested that only one quantity be used for dosimetry, i.e. the reference air kerma rate. With the use of a single quantity the amount of confusion would be reduced.

If a conversion from one unit to another must be done, a consistent set of conversion factors should be used. The subject of consistency is complicated and great care should be taken when using conversion factors. This can be exemplified by the following; the calibration performed by the manufacturer is traceable to a standards laboratory, but the source strength on the certificate, is given using some other quantity. If there is a need to convert the quantity on the certificate, it must first be converted back to the traceable quantity using the same conversion factor as that used by the manufacturer. After this, a conversion to the desired quantity can be done. If this procedure is not followed, but the source strength given on the certificate is converted using another factor than that used by the manufacturer, the traceability of the source is lost.

The matter is further complicated if the dose planning system requires the source strength to be specified in some quantity, but for dose calculation purposes makes a conversion to another quantity. In this case, the documentation of the dose planning system must be consulted in order to determine the value of the conversion factor. With regard to these examples, it is easy to understand why severe accidents have occurred in this field.

When the source strength is entered into the dose planning system, the dose calculated with the system should be quality controlled. This can be done by calculating the dose at a well specified point using exact co-ordinates. The dose should then be compared with manual calculations, using a well established method. In the manual calculation of the dose, the source strength should be specified in terms of the traceable quantity, irrespective of the quantity that was entered into the dose planning system. The calculation should be done at a short distance, between 1 cm and 2 cm, because at these distances different calculation methods are, at least for ^{192}Ir, ^{137}Cs and ^{60}Co, in good agreement with one another, generally within 1%–2%. At larger distances the methods might differ, often due to different models for scatter and absorption correction, the effect of which is small at short distances.

It is not the purpose of this report to focus on problems associated to the clinical use of brachytherapy sources. These have been addressed in detail in a recent IAEA report [27]. Therefore, the QC in the present report is limited to the calibration of brachytherapy sources, to the QC of the equipment used in the calibration and to the safety aspects related to the calibration procedures.

5.2. Well type chamber characteristics

Well type chambers provide a reliable method for calibrating brachytherapy sources before clinical use. There are at least two types of well type chambers that are used in many hospitals. High pressure gas (usually argon) filled chambers which were designed originally for assaying low activity radio-nuclides and well type chambers that are open to the atmosphere. Loss of pressure due to gas leakage affects the sensitivity of the former type of chamber. Unlike chambers that are open to the atmosphere, such chambers do not require corrections for changes in the ambient temperature and pressure.

The insertion of a very high activity ^{192}Ir HDR source, can cause a temperature increase inside the chamber [28]. Some chambers are designed with a Styrofoam insert to reduce this effect. The response of the chamber should be checked at regular intervals using a source of long half life. A ^{137}Cs source is suitable for this purpose although other sources might be available. The source should be inserted into the chamber with appropriate spacer and/or holder in a reproducible way. Readings from use of the constancy source corrected for temperature, pressure and decay of the source should remain within $\pm 0.5\%$. The sensitivity of

the chamber should be measured as a function of the depth of insertion of the source from the bottom of the chamber. The characteristic shape of this positional dependency depends upon the chamber design. A typical sensitivity plot is shown in Fig. 8.

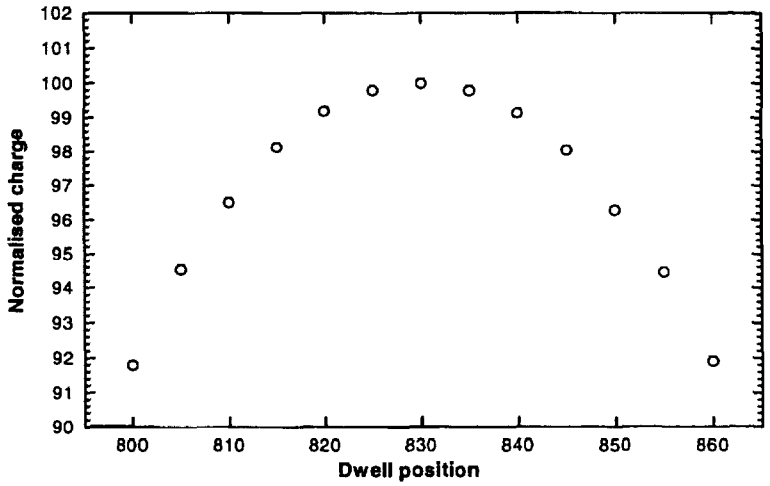

Figure 8. Normalized charge versus source dwell position in a well type ionization chamber.

Well type chambers respond to scattered radiation and should be used away from walls that might scatter radiation back to the chamber. Experimental determination of this effect might be required. For most chambers, providing the chamber is at least 30 cm from the nearest wall, the effect of scatter is negligible.

Typical characteristics needed in HDR source calibrations include high ion collection efficiency for currents of about 10 nA and high positional reproducibility for the source.

5.2.1. Source storage and handling of LDR sources

Suitable source storage containers are commercially available but can also be locally made. Whatever container is used, the dose equivalent rate at accessible distance from the surface of the container should not exceed 20 μSv/h.

A lead-shielded work bench and handling tools can be used for the safe handling of the sources. In the case of ^{137}Cs LDR reference sources, the sources should be loaded into Perspex tubes for the ease of handling and to minimise radiation exposure. A cylindrical lead storage container, illustrated in Fig. 9, that is used at the IAEA Dosimetry Laboratory to store the ^{137}Cs reference sources. The container has two metallic tubes near the centre to place the source holders.

5.3. Stability checks of the well type chamber

5.3.1. ^{137}Cs reference source check

At least one of the ^{137}Cs reference sources should be used to check the constancy of the well type chamber calibration. The source should be inserted in the chamber with the appropriate spacer under reproducible conditions as mentioned in prior sections. The reading from the reference source corrected for temperature and pressure and for the decay of the source should remain within $\pm$0.5%.

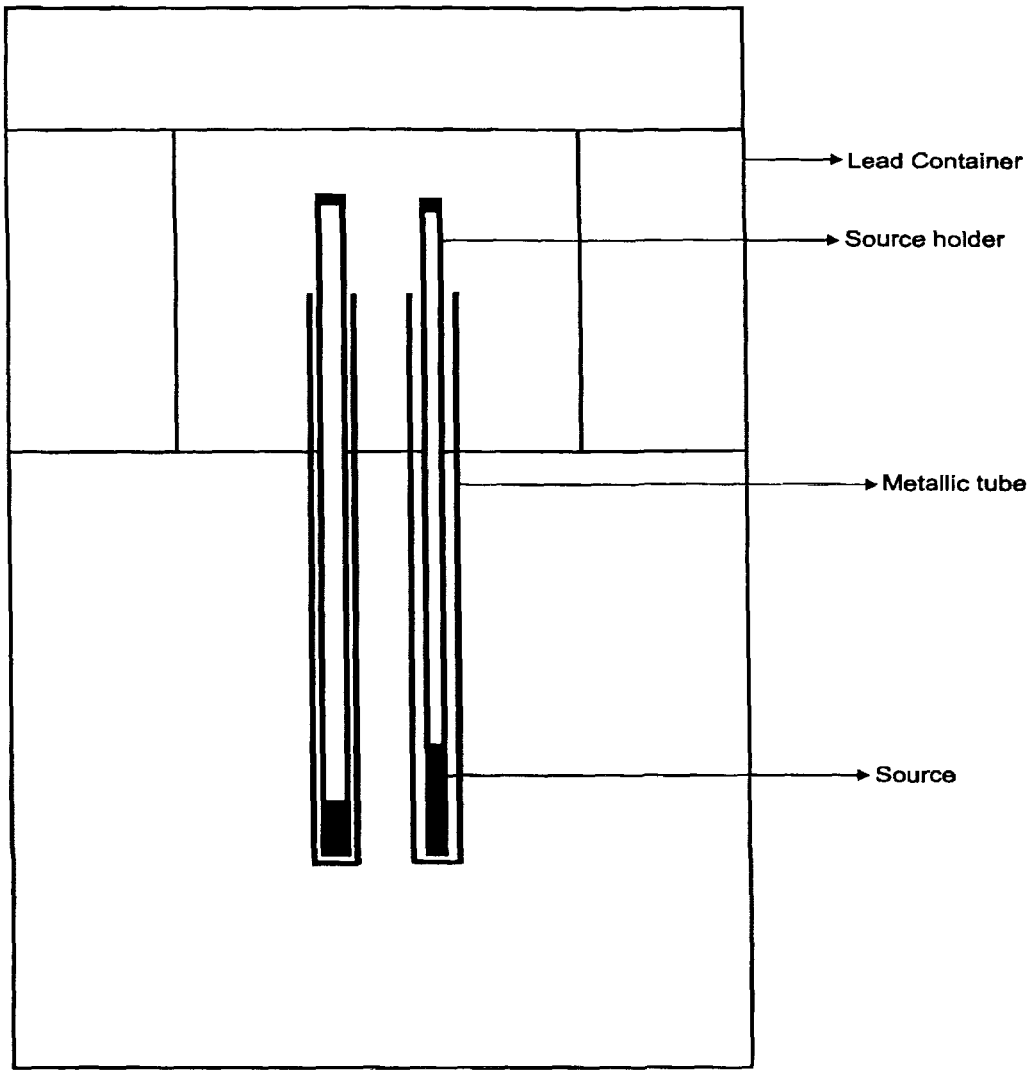

Figure 9. Lead storage container used at IAEA Dosimetry Laboratory. The container has two metallic tubes in the centre, where the source holders are inserted.

5.3.2. ^{60}Co beam check

The top surface of the well type chamber should be set to an appropriate SSD (source surface distance), e.g. 100 cm for the external beam ^{60}Co unit of the SSDL. The field size should be larger than the diameter of the chamber, e.g., 15 cm × 15 cm (Fig. 10). A dose of 1 Gy should be delivered to the surface of the chamber. After correcting for temperature and pressure and decay the reading of the chamber should remain constant within ±1.0%. Ensure that the dose of 1 Gy is constant.

5.3.3. Other constancy checks

Other constancy checks may be performed if equipment is available. For example, a low activity ^{241}Am source of the type used for constancy tests of large volume ionization chambers may be inserted in the well type chamber and constancy established.

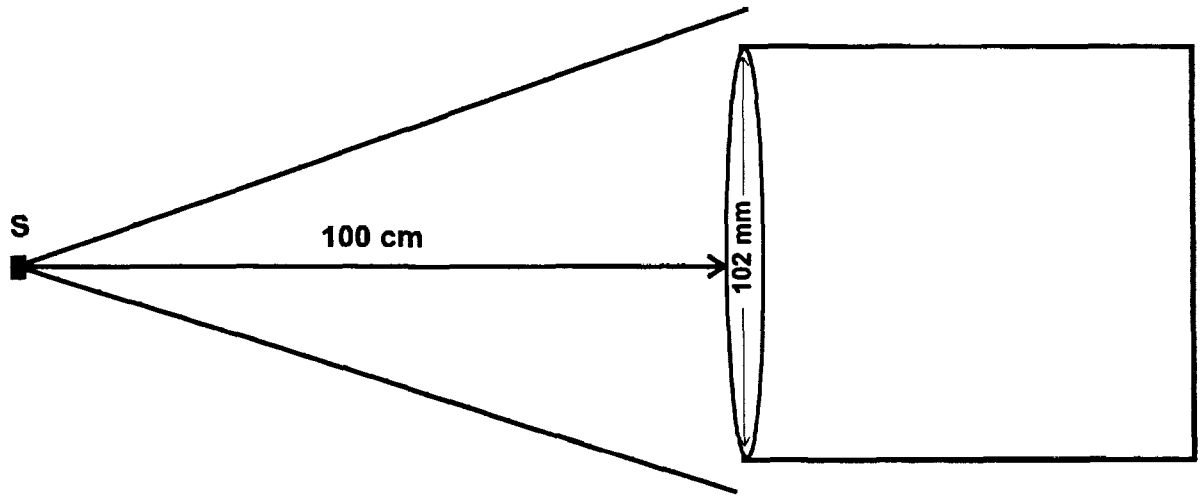

Figure 10. Alignment of well type chamber for stability check in ^{60}Co beam.

5.4. Radiation safety

5.4.1. Leakage testing of the ^{137}Cs reference sources

The leakage of the reference sources should be tested by wet wipes every time a new reference source is received and in connection with each replacement of the Perspex insert tubes. With the help of the source handling tongs to minimise the radiation exposure of the operator, the source is wiped with a swab or tissue, moistened with methanol or water and the activity removed is measured. The wipe can be measured by a contamination monitor or gamma-spectrometric equipment, sensitive enough to detect the acceptable limit of 0.18 kBq. The leakage test should be done by an experienced Radiation Safety Physicist.

5.5. Other precautions

Since the continuous exposure of the Perspex insert tubes to radiation makes them delicate and prone to breakage, it is recommended that they are replaced every six months and in no case, less often than once a year.

The sources shall be marked so that they can be easily identified. An up-to-date inventory of the sources must be kept and their storage marked with appropriate signs of radiation hazard. A general purpose survey meter must be available for monitoring of radiation levels near the sources and their containers.

5.6. Maintaining the traceability

As a regular monitoring of the traceability of the brachytherapy calibrations at the SSDLs, a re-calibration of the SSDL well type chamber is recommended at least every five years, or if the results of the constancy tests suggest a change in the sensitivity of the well type chamber.

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