Recommendations for the Calibration of Iridium-192 High Dose Rate Sources

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

Report 7 of the Netherlands Commission on Radiation Dosimetry

Netherlands Commission on Radiation Dosimetry
Task Group Dosimetry of Iridium-192 High Dose Rate Sources
December 1994

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Authors:

J.L.M. Venselaar

A.H.L. Aalbers

W.F.M. Brouwer

H. Meertens

J.J. Petersen

B. Schaeken

A.G. Visser

Netherlands Commission on Radiation Dosimetry

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Preface

The Nederlandse Commissie voor Stralingsdosimetrie (NCS, Netherlands Commission on Radiation Dosimetry) was officially established on 3 September 1982 with the aim of promoting the appropriate use of dosimetry of ionizing radiation both for scientific research and practical applications. The foundation is chaired by a board of scientists, installed upon the suggestion of the supporting societies, including the Nederlandse Vereniging voor Radiotherapie (Netherlands Society for Radiotherapy), the Nederlandse Vereniging voor Nucleaire Geneeskunde (Netherlands Society for Nuclear Medicine), the Nederlandse Vereniging voor Klinische Fysica (Netherlands Society for Clinical Physics), the Nederlandse Vereniging voor Radiobiologie (Netherlands Society for Radiobiology), the Nederlandse Vereniging voor Stralingshygiëne (Netherlands Society for Radiological Protection), the Kring Stralingsfysica (Netherlands Group of Radiation Physicists) and the Ministry of Welfare, Health and Cultural Affairs.
To pursue its aims the NCS accomplishes the following tasks: participation in dosimetry standardisation and promotion of dosimetry intercomparisons, drafting of dosimetry protocols, collection and evaluation of physical data related to dosimetry. Furthermore the commission shall maintain or establish links with national and international organisations concerned with ionizing radiation and promulgate information on new developments in the field of radiation dosimetry.

RECOMMENDATIONS FOR THE CALIBRATION OF IRIDIUM-192 HIGH DOSE RATE SOURCES

Prepared by a taskgroup of the Netherlands Commission on Radiation Dosimetry (NCS) in cooperation with the Belgian Association of Hospital Physicists (S.B.P.H./B.V.Z.F.).

Members of the taskgroup:

J.L.M. Venselaar, chairman
A.H.L. Aalbers
W.F.M. Brouwer
H. Meertens
J.J. Petersen
B. Schaeken
A.G. Visser

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1. Introduction

In 1989 the Nederlandse Commissie voor Stralingsdosimetrie, NCS, (Netherlands Commission on Radiation Dosimetry) issued its Report No. 4: "Aanbevelingen voor Dosimetrie en Kwaliteitscontrole van Radioactieve Bronnen bij Brachytherapie" (in Dutch). The contents of this report was summarized in the English language in: "Recommendations for Dosimetry and Quality Control of Radioactive Sources used in Brachytherapy"; Report 4, Synopsis, NCS, February 1991 [20]. In this report attention was mainly directed towards the dosimetric quality control of brachytherapy sources generally in use with low dose rate (LDR) techniques. Furthermore, several aspects of the radiological protection of the patient, personnel and visitors were discussed; in the appendices an overview was given of the relations between the radiological SI-units and other non-recommended older radiological units, as well as specific recommendations for the quality control of treatments with specific types of sources.

The number of high dose rate (HDR) brachytherapy afterloading machines has significantly increased in the last few years in The Netherlands and Belgium, as well as elsewhere in the world. Almost all new HDR installations were equipped with iridium-192 sources, having a typical source strength of 370 GBq. Due to the relatively short half-life of iridium-192 of approximately 74 days, sources have to be exchanged every 3 to 4 months. This makes the quality control of the source delivery a routine procedure, in contrast to the quality control of sources with a longer half-life such as cobalt-60 and caesium-137.

In the above mentioned NCS Report 4 it is recommended to pursue an uncertainty in the dose specification for brachytherapy due to physical procedures of less than 5% (1 sd). The calibration of a source itself is only part of these procedures. An error in the value of the source strength systematically introduces errors in the dose determination for all patients treated with the source. It is clear that this error should be kept as low as possible and, based on the published experiences up to now, the recommendation to pursue an uncertainty in this step of less than 2% (1 sd) seems therefore justifiable. For at least two manufacturers of iridium-192 HDR afterloading equipment[1,2], Mallinckrodt Diagnostica Holland BV[3] is the supplier of the sources. At present, this company provides a calibration certificate in terms of an equivalent activity for each source of "10 Ci (370 GBq) as of calibration date" with a stated accuracy of ± 10%. This activity calibration, which is deduced from "the measured radiation output of the

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1 MicroSelectron HDR, Nucletron Trading BV, Veenendaal, The Netherlands

2 Gammamed 12i, Isotopen-Technik Dr. Sauerwein GMBH, Haan/Rheinl., Germany

3 Mallinckrodt Diagnostica Holland BV, Petten, The Netherlands

sealed source", is at this moment not traceable to any National Standards Laboratory. Several investigations (e.g. [3, 7, 9, 28]) have shown that in a significant number of cases the measured source strength deviates by more than the clinically desired ± 5% (for all steps in the physical procedures!) from the value of the calibration certificate. A few cases were reported with deviations even outside the stated limits of ± 10% [3].
Based on these data the necessity to perform an in-house calibration of each new source is clear. The source strength value obtained in such a calibration should be used for subsequent clinical applications. The calibration should be performed before patients are treated with the source.

Although several publications (e.g. [4, 5, 8, 12]) have dealt with Ir-192 dosimetry, a generally accepted protocol from one of the national or international committees is not yet available. There still is some confusion on matters as: the best calibration method, the derivation of the appropriate N_K-factor for an ionization chamber for iridium-192 photon radiation, the choice of optimal distance from source-to-detector, the use of a build-up cap and the application of certain correction factors. This confusion was apparent in the results of a recently performed comparison of calibration procedures in The Netherlands and Belgium [28].

The purpose of the present report is to recommend uniformly applicable calibration methods, feasible in each clinical situation, in order to achieve more consistency between the users of high dose rate afterloading equipment. The traceability to the National Standards Laboratory[1] is emphasized.

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1 In The Netherlands: The Netherlands Measurements Institute (NMi), Delft; In Belgium the Rijks Universiteit Gent is the acting Standards Laboratory and will be accredited by the Belgian Calibration Organization (B.K.O.).

2. Quantities, units and definitions

Reference Air Kerma Rate: the air kerma rate of a source at a distance of 1 m, free in air, corrected for the attenuation and scattering in air. It is expressed in the unit $\mu Gy.h^{-1}$.

Reference Exposure Rate: the exposure rate of a source at a distance of 1 m, free in air, corrected for the attenuation and scattering in air. It is expressed in the unit $C.kg^{-1}.h^{-1}$.

Effective or Apparent Activity: the activity of a non-shielded point source of the same nuclide, that would give the same air kerma rate at a reference distance of 1 m from the source. The unit is GBq.

The latter two quantities are superfluous if the source specification method recommended in this report is used. Use of the quantities Reference Exposure Rate and Effective or Apparent Activity is therefore not recommended.

Following the recommendations of the NCS Report 4, the strength of a brachytherapy source should be specified in terms of the reference air kerma rate ($\dot{K}_{ref}$) in the unit $\mu Gy.h^{-1}$ [20].

Comment:
From a theoretical point of view the ideal quantity of interest to specify the strength of a source is "dose to water at a short and clinically relevant distance (e.g. 20 - 50 mm) from the source". However, there are at present no methods available with which the source strength could be measured directly in this quantity as a routine procedure. Thus, until new methods become available, one has to use other, more indirect methods to determine the source strength.

3. Techniques for the calibration of the source

3.1 *General comments*

Three methods are discussed in the next sections. The first two methods are based on the use of a small (e.g. 0.6 cm^3 Farmer-type) ionization chamber, which is also used for the calibration of megavoltage photon beams. These techniques can either be applied as an **in-air measurement**, e.g. using an in-air calibration jig as described elsewhere (e.g. [4]) and supplied by manufacturers of HDR afterloading equipment, or as an **in-phantom measurement** using a solid phantom. The third method is based on the use of a calibrated **well-type chamber**. This technique is similar to the one used for the calibration of (low activity) sources in nuclear medicine.

The in-air measurement technique is quite straightforward. This method determines the source strength in the desired quantity: air kerma rate at a certain distance, from which the reference air kerma rate is deduced. The measurement can be performed with commercially available equipment or with an in-house constructed calibration jig. The correction factors, needed to derive the reference air kerma rate from an ionization chamber measurement, can partly be taken from the literature and partly be determined by experiment.

The use of a solid phantom for brachytherapy calibrations has the advantage that measurements in a such a phantom can be performed in any room where radiation protection regulations allow the application of HDR sources, i.e. a scatter free environment is not required. A second advantage is that the geometrical accuracy of the source-detector geometry in a solid phantom can be assured rather easily and that the measuring setup is more rugged in comparison to the setup for in-air measurements. More precise calibrations can therefore be expected.

A disadvantage of in-phantom measurements is that, in comparison to in-air measurements, some additional correction factors are required in order to convert the reading of the instrument to the desired quantity (reference air kerma rate). Not all correction factors are known to the required high degree of accuracy for iridium-192 sources. Comparisons of in-air and in-phantom calibration results indicate that in-phantom measurements are certainly feasible and can be used as a good alternative to in-air calibrations [27].

Well-type chamber measurements are often applied for low-activity sources in nuclear medicine. The much higher strength of HDR sources requires the use of a dedicated piece of

equipment. Only very recently, well-type chambers, specifically designed for use with iridium-192 HDR sources, have become commercially available. Measurements with a well-type chamber are relatively simple and quick to perform, but attention must be paid to factors such as source (re-)positioning, chamber calibration, ion-recombination, linearity and long-term stability.

The use of the in-air measurement technique for in-house calibration of an iridium-192 HDR source is recommended in this report: the desired quantity is measured directly; the correction factors to be applied are known to a sufficiently high degree of accuracy; except for the calibration jig, no special equipment is necessary, because the institute's secondary standard ionization chamber is used. The chamber itself can be calibrated at the National Standards Laboratory for the gamma-ray spectrum of the source.
Nevertheless, the advantages and the value of the other two techniques, certainly for routine measurements, are acknowledged. If one of these techniques is used, it is mandatory to establish the traceability to the in-air method by intercomparisons using the same source(s).

A new development which needs special attention is the introduction of PDR (Pulsed Dose Rate) afterloading equipment. This type of afterloader operates with a source strength which is in general much smaller than the source strength of HDR machines, typically 1/10 of it (37 GBq). Also, the source construction is different, which is reflected in different anisotropy characteristics. With respect to the calibration of this type of source, it is recommended here to follow the same procedures as with HDR sources.

Regardless of the method used to calibrate the sources, it is recommended to measure each source at least twice: at the moment of acceptance of a new source and after final use of each source (just before acceptance of the new source). In this way, an additional check of the stability of the measuring equipment is obtained, correcting only for source decay.

In the following sections the above mentioned methods are discussed in more detail. Values of correction factors are given between brackets, which are specific for the recommended measurement conditions such as chamber dimensions, source-to-chamber distance, exposure time and use of a specific phantom. Whenever other conditions prevail or other phantoms are used, these values may change correspondingly!

3.2 *In-air measurements*

It is recommended to make use of the calibration services offered by the National Standards Laboratory for the calibration of ionization chamber instruments. The calibration factor of the measuring device is expressed in the units air kerma per unit reading. It is recommended to use as a measuring device the institute's standard equipment, e.g. the institute's secondary standard ionization chamber in combination with its electrometer. For routine use, other instruments may be used, with traceability to the in-house secondary standard. These field instruments can be used, provided they are checked against the secondary standard in exactly the same geometry and using the same measurement conditions.

The calibration of the ionization chamber at the National Standards Laboratory for the iridium-192 gamma-ray spectrum is performed with the recommended build-up cap, in use for cobalt-60 gamma rays. Such a build-up cap is also necessary to eliminate contaminating electrons originating from the encapsulation of the iridium-192 source [8].

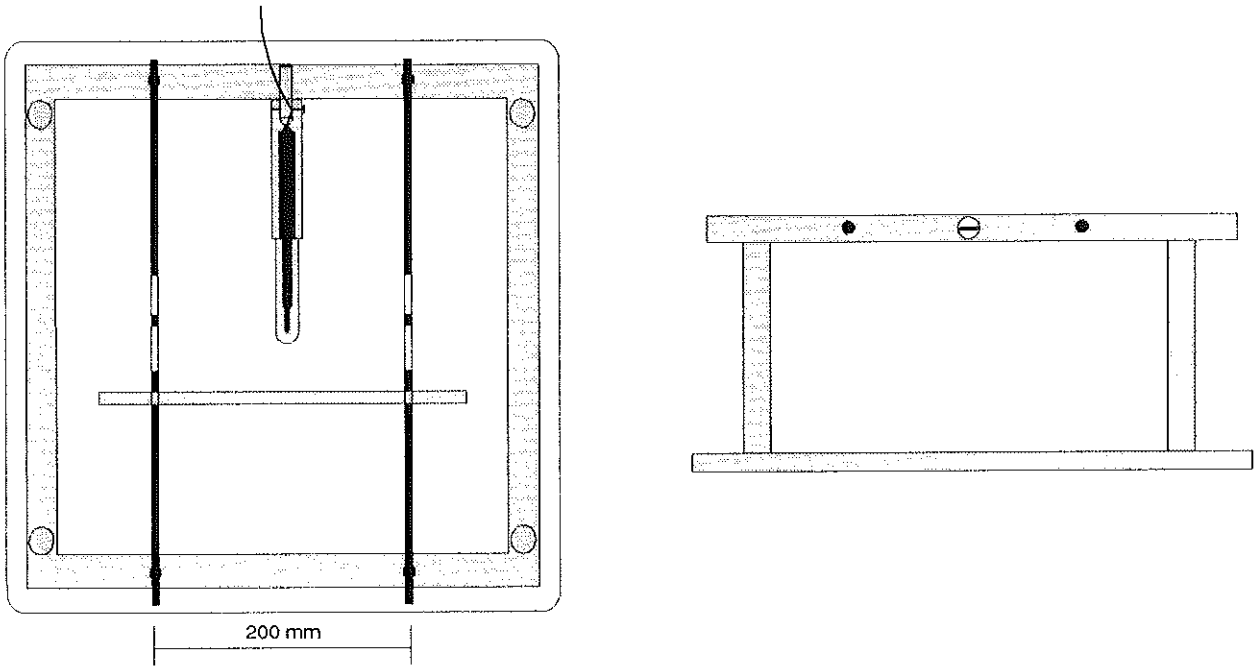

Figure 3.1. *Top and side view of a calibration jig for in-air measurements. The source is positioned in the two catheters, at a distance of 0.100 m from the centre of the ionization chamber. A thin (≤ 5 mm) stabilisation rod improves rigidity, but has no influence on the value of the room scatter correction factor, f_{rs}.*

It is recommended to use a dedicated in-air calibration jig. The jig should be stable and rigid, allowing a reproducible repositioning of the ionization chamber and the source catheter(s). The distance between the ionization chamber and the massive parts of the jig should be at least 200 mm in order to minimize the contribution of radiation scattered from the surroundings. A double catheter system, where each catheter is placed at the same distance on either side of the chamber, is preferred. This setup provides a common point midway between the catheters at which the reading can be averaged. Attention should be paid to the rigidity of such a system. Sometimes rigidity can be improved by using thin stabilisation aids to the jig. A possible jig design is shown in figure 3.1. A measuring distance of 100 mm is recommended. The afterloading machine should be programmed to sequentially position the source in each of the catheters.

The reference air kerma rate $\dot{K}_{ref}$ (μGy.h^{-1}) can be obtained from the in-air measurement using the following expression

$$\dot{K}_{ref} = \frac{M \cdot N_K \cdot \Pi f_i \cdot d^2}{t}$$

where

$$M = M_{uncor} \cdot p_t \cdot p_p \cdot p_{hum} \cdot p_{ion} \cdot p_{pol} \cdot p_{nu}$$

with

M	: corrected instrument reading, integrated over the time period t;	
M_{uncor}	: uncorrected instrument reading;	
p_t	: air temperature correction factor for the reference temperature at which N_K is determined;	
p_p	: air pressure correction factor for the reference air pressure at which N_K is determined;	
p_{hum}	: air humidity correction factor;	(1.000)[1]
p_{ion}	: ion recombination correction factor;	(1.000)
p_{pol}	: correction factor for polarity effects;	(1.000)

1 Values given may only be valid for the specified measurement conditions; whenever these conditions change, values may change correspondingly!

p_{nu} : corrects for the dose non-uniformity over the chamber wall and is calculated from data given by Kondo and Randolph [14]; (1.006)

N_K : (μGy per unit reading) is the air kerma calibration factor for the ionization chamber for the iridium-192 gamma-ray spectrum;

where

$$\Pi f_i = f_{tr} \cdot f_{rs}$$

f_{tr} : correction factor for source transport time (t > 600 s or 0.1667 h); (1.000)

f_{rs} : correction factor for room scatter for a wall to chamber distance of 0.5 m or more; (0.999)

and where

d : source-to-chamber axis distance for the jig as described; relative to the reference distance of 1 m; (0.100)

t : total exposure time (in h) of the measurement with the source at its position in each of the two catheters; (0.1667)

M_{uncor} is the average of repeated readings; because of the relatively low air kerma rate at the point of measurement, it may be necessary to correct the readings for the meter-offset and the leakage current of the ionization chamber in combination with the electrometer.

p_{nu} corrects for the dose gradient that exists when a chamber of finite dimensions is used in a region of sharp dose gradient. p_{nu} is dependent on the dimensions of the chamber and on the distance from source to chamber. It is recommended to use a multiplicative factor to correct the reading for this effect as described elsewhere [14]. For a Farmer type ionization chamber (0.6 cm^3, length 24 mm and diameter 6 mm) the correction factor calculated from this work, is tabulated here as a function of the distance from the centre of the source to the geometrical centre of the chamber.

Table 3.1.: Values of the dose non-uniformity correction factor, p_{nu}, as a function of the distance from the source to the centre of the chamber with the specified dimensions.

d (mm)	p_{nu}
20	1.107
50	1.019
100	1.006
150	1.003
200	1.001

For other chamber dimensions the reader is referred to the original paper [14].

N_K is the air kerma calibration factor of the ionization chamber with build-up cap in combination with the electrometer for the iridium-192 gamma-ray spectrum, determined at the National Standards Laboratory. N_K is expressed in μGy per unit reading. The method presently in use at the NMi to determine the N_K factor for this spectrum, a weighting method over the complete spectrum, is described elsewhere for two types of ionization chambers (NE 2561 and NE 2571) [23]. Other chambers can be calibrated using the same method.

Because the chamber is irradiated during the transport time of the source to the dwell position in the catheter, a correction has to be made to the total reading. This correction factor f_{tr} can be derived from

$$f_{tr} = 1 - \frac{M_{t0}}{M_t}$$

where

M_{t0} : extrapolated reading for $t = 0$;

M_t : reading for the exposure time t for which f_{tr} is calculated.

The reading for $t = 0$, M_{t0}, is obtained from linear extrapolation from the readings taken for different exposure times. Alternatively, an external timer to the electrometer can be used in order to obviate any transport time corrections.

f_{rs} corrects for the additional radiation that is detected by the ionization chamber originating from scatter by the surrounding materials: jig, floor and walls of the room. f_{rs} depends on the

construction of the jig, the distance from the source to the detector and on the distances from the walls and/or floor of the room to the detector. The importance of the correction factor f_{rs} increases with increasing distance, d, from the source to the detector. Methods to determine its value are described elsewhere [4, 8], all based on measurements at different source-to-chamber distances. It is recommended to perform these measurements for a particular geometry, or to take a value from the literature. From Table 3.2. it is clear that there is a good agreement between the values reported for the calibration jigs, and the source-to-detector distances of interest.

Table 3.2. Values of the room scatter correction factor, f_{rs}, as a function of the distance from the source to the centre of the chamber.

d (mm)	f_{rs} Gooetsch et al [8]	Ezzell [4]	Venselaar et al [28]
50	-	1.000	-
100	0.9985	0.999	0.9987
150	0.9965	0.997	-
200	0.9937	0.994	-
250	0.9901	-	-
300	0.9858	0.988	-
350	0.9807	-	-
400	0.9753	-	-
500	-	0.966	-

The reading of an electrometer generally does not change significantly when the distance of the jig and the chamber to the walls or floor is increased from approximately 0.50 m; in practice it is easy to keep this distance during all measurements to at least 1.00 m.

Measurements may be performed with a source-to-chamber distance (d) in the range of approximately 100 to 200 mm [6]. The low end of this range is dictated by possible errors in the calibration due to errors in determining the distance and due to the gradient effect; for larger distances the exposure rate may decrease to a too low value, while the room scatter contribution increases to several per cent and the leakage of the electrometer may also cause some problems. A source-to-chamber distance d = 100 mm (0.100 m) is recommended in this report; in the expression to calculate the reference air kerma rate, d is taken relative to the reference distance of 1 m.

The exposure time at each measurement is not critical. An optimum choice may be dictated by the equipment. With a small value of t, the measurement can be repeated several times and the readings may be averaged. If a relatively large value of t is used, the correction factor f_{tr} becomes 1.000. In all cases one has to check whether the electrometer reading is significantly influenced by leakage, in which case a correction may be needed. A time t = 600 s (0.1667 h) is recommended in this report.

The influence of air attenuation is neglected here as it is only a very small correction when applied to measurements at a distance of 100 mm. Rossiter et al., for example, used an air attenuation correction of 0.2 % per meter [26].

3.3 *In-phantom measurements*

Experience with in-phantom source measurements has been obtained for different types of brachytherapy sources, namely sets of caesium-137 spherical sources used in the Selectron-LDR afterloading machine [15] and sets of cobalt-60 sources used in the Selectron-HDR machine. For these measurements a cylindrical PMMA (polymethylmethacrylate) phantom was used containing a Farmer-type 0.6 cm^3 ionization chamber, positioned along the axis of the phantom and three applicators placed symmetrically (at 120° angles) in channels parallel to the central axis at an axis-to-axis distance of 50.0 mm. The height of this PMMA cylinder was 150 mm and the diameter was 200 mm. The procedure to calibrate a set of Selectron-LDR sources has also been described in NCS Report 4 [20].

A phantom of this type is also adequate to calibrate the single source of an iridium-192 HDR brachytherapy afterloader. See figure 3.2. The size of the applicator channels in the phantom should of course be modified to accept HDR afterloading catheters. The afterloading machine should be programmed to sequentially position the source in each of the three catheters, with positions located in a plane through the geometrical centre of the ionization chamber.

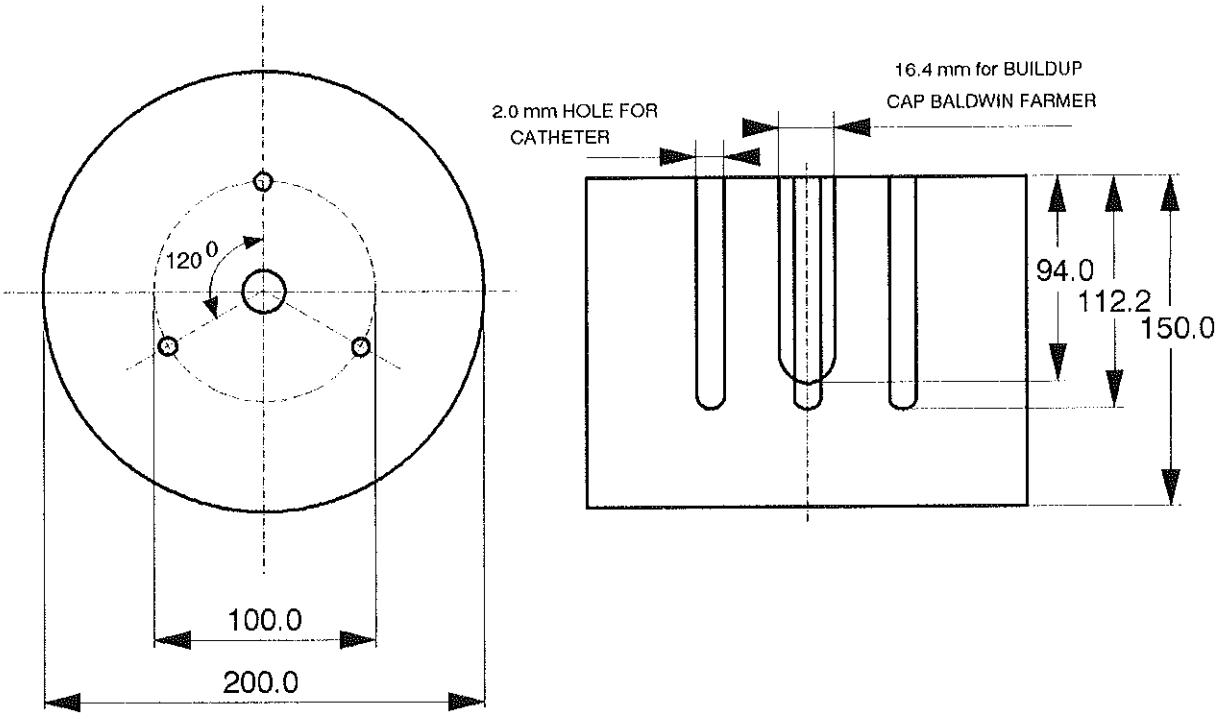

Figure 3.2. *Construction drawing (top and side view) of the PMMA calibration phantom for in-phantom measurements, as discussed in this section. Dimensions are given in mm.*

The reference air kerma rate $\dot{K}_{ref}$ (μGy.h^{-1}) can be obtained from the in-phantom measurement using the following expression

$$\dot{K}_{ref} = \frac{M \cdot N_K \cdot \Pi k_i \cdot \Pi p_i \cdot \Pi f_i \cdot d^2}{t}$$

where

$$M = M_{uncor} \cdot p_t \cdot p_p \cdot p_{hum} \cdot p_{ion} \cdot p_{pol} \cdot p_{nu}$$

with

M	: corrected instrument reading;	
M_{uncor}	: uncorrected instrument reading;	
p_t	: air temperature correction factor;	
p_p	: air pressure correction factor;	
p_{hum}	: air humidity correction factor;	(1.000)[1]
p_{ion}	: ion recombination correction factor;	(1.000)
p_{pol}	: correction factor for polarity effects;	(1.000)
N_K	: (μGy per unit reading) is the air kerma calibration factor for the photon spectrum of iridium-192;	

and where

$$\Pi k_i = k_w \cdot k_{st} \cdot k_{ce}$$

k_w	: correction factor for the attenuation and scatter in the chamber wall and build-up cap during calibration; it is the ratio of the kerma inside the chamber to that at the same location in free space [8];	(0.984)
k_{st}	: correction factor for the stem effect for the employed geometry during calibration;	(1.000)
k_{ce}	: correction factor for the effect of the central electrode on the response of the chamber during calibration,	(1.000)

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1 Values given may only be valid for the specified measurement conditions; whenever these conditions change, values may change correspondingly!

and where

$$\Pi p_i = p_r \cdot p_{ce}$$

p_r	: correction factor for the replacement of PMMA by the ionization chamber;	(1.016)
p_{ce}	: correction factor for the effect of the central electrode on the response of the chamber during the measurement in the phantom,	(1.000)

and where

$$\Pi f_i = f_{tr} \cdot f_{ph} \cdot f_{geo}$$

f_{tr}	: correction factor for source transport time ($t > 600$ s);	(1.000)
f_{ph}	: conversion factor from the specified PMMA phantom (diameter 200 mm, height 150 mm) to a full-scatter water phantom for the iridium-192 spectrum;	(1.033)
f_{geo}	: correction factor for absorption and scatter in water;	(0.9941)

finally

d	: source-to-chamber distance for the phantom as described; relative to the reference distance of 1 m;	(0.05)
t	: total exposure time (in h) of the measurement with the source at its position in each of the three catheters.	(0.1667)

M_{uncor}, N_K, and f_{tr} are discussed before, in section 3.2.

The correction factor k_w has a value of 0.984 for a total wall thickness of 0.6 g.cm^{-2}, which includes the recommended cobalt-60 build-up cap [8]. For a smaller total wall thickness of 0.31 g.cm^{-2} the value of k_w becomes 0.992.

The replacement correction factor p_r is the ratio of the ionization rate per unit mass in an air volume approaching zero at the point of measurement in the phantom and the average ionization rate per unit mass of the air volume of the actual ionization chamber when the geometrical centre of the air volume coincides with the point of measurement. For the recommended geometry p_r = 1.016 [27].

The conversion factor f_{ph} from the PMMA phantom, with physical dimensions described in section 3.3., to the full-scatter water phantom, corrects the reading for the difference in electron density of PMMA and water and the loss of scatter due to the finite size of the phantom. f_{ph} can be derived by measuring the source strength in an identical source ionization chamber geometry in a full-scatter water phantom. For the cylindrical configuration described, f_{ph} is 1.033 [27]. The factor f_{ph} can be separated in a water to PMMA conversion factor f_{wp} (1.004) and a (lack of) scatter correction factor f_{sc} (1.029). From the values of these factors we see that the scatter correction is the major effect. It is emphasized therefore that any other choice of the size of the phantom definitely leads to a change in this correction factor.

The conversion factor f_{geo} converts the air kerma rate in the phantom to air kerma rate free in air taking scatter and attenuation into account according to the polynomial expression proposed by Meisberger et al. [16]. Its value is, for this specific geometry with a source-to-chamber distance of 50 mm,

$$f_{geo} = \frac{1}{S(d)} = \frac{1}{1.0059} = 0.9941$$

An exposure time t = 200 s for the dwell position in each catheter (3 x 200/3600 = 0.1667 h) is recommended in this report for a source with a reference air kerma rate of about 1 to 4 cGy.h^{-1}.

No correction factor is applied for attenuation in air; see section 3.2.

3.4 *Well-type chamber measurements*

A well-type ionization chamber may be used for relative source strength measurements of iridium-192 HDR sources. Calibration of such a chamber requires a source of known strength. The calibration is an 'in-house' calibration with a source of which the absolute strength has been determined by one of the methods described in sections 3.2. and 3.3. or by the National Standards Laboratory; the latter method is recommended. It is important that both the geometry in which the chamber is placed and the positioning of the source inside the well are identical during calibration and source strength measurements.

There are special requirements for well-type chambers to be used for iridium-192 HDR source strength measurements. Matters of concern are linearity, magnitude of the ionization signal, thermal gradients due to source heating and material thickness between the source and the ion collecting volume. Although other well-type chambers can be used for iridium-192 HDR source strength measurements, it is recommended to use a chamber specially designed for this purpose. Other well-type chambers require additional corrections, resulting in a larger uncertainty in the source strength. Several types of well-type chambers for iridium-192 HDR measurements are commercially available [10].

For calibration of the well-type chamber, the reading obtained from the calibrated source is determined as if a source strength determination has to be performed. The "in-house" calibration factor, N_K, is obtained from the following formula.

$$N_K = \frac{\dot{K}_{ref} \cdot t}{M \cdot f_{tr}}$$

where

$$M = M_{uncor} \cdot p_t \cdot p_p$$

with

M : corrected instrument reading;

M_{uncor} : uncorrected instrument reading;

p_t : air temperature correction factor;

p_p : air pressure correction factor;

N_K : "in-house" calibration factor of the well-type chamber in μGy per unit reading;

t : exposure time of the measurement with the source at its position inside the well chamber;

f_{tr} : correction factor for source transport time.

Once the well-type chamber has been calibrated, source strength measurements can be performed. The source strength, expressed in terms of reference air kerma rate, can be calculated from the reading M using the same expression, now written as:

$$\dot{K}_{ref} = \frac{M \cdot N_K \cdot f_{tr}}{t}$$

The above expressions can be simplified when a sealed chamber is used; the amount of gas in the sensitive volume will be constant for all measurements so the correction for air temperature, p_t, and air pressure, p_p, can be omitted.

The "in-house" calibration factor of the well-type chamber, N_K, is defined as the strength of the calibrated source (in reference air kerma rate at a reference distance of 1 m) multiplied with the exposure time, divided by the (corrected) electrometer reading. The dimension of the calibration factor is μGy per unit reading.

Calibration of an iridium-192 HDR source can be performed at the institute by the National Standards Laboratory. The method used by the NMi is described elsewhere [22].

The experimental setup in which the chamber is situated influences the response [24]. Radiation scattered from the surroundings will increase the measured signal. Because relative measurements are concerned here, exact knowledge of the amount of scatter radiation is not important; consistency should, however, be maintained.

To ensure reproducible positioning of the source inside the well, usually a jig is supplied with the chamber. A catheter can be inserted inside the jig and secured. The best place in the well to locate the source is at the point of maximum response. Around this point the response of the chamber is almost constant, which makes the measurement less sensitive to small variations in positioning. It is recommended to check the variations in the response of the chamber around the point of maximum response.

The primary cause of non-linearity of a well-type chamber is volume recombination. The high source strength of an iridium-192 HDR source causes a high ionization density in the sensitive volume. It is desirable that the well-type chamber used for iridium-192 HDR source strength measurements has minimal volume recombination. It is recommended to check the magnitude of the recombination by measuring the response of the chamber to a source of clinical strength at (at least) two polarizing voltages. If the difference in response is marginal, no recombination correction is necessary. The high source strength also limits the size of the ion-collecting volume. A large sensitive volume will give an ionization current that exceeds the range of most commonly used electrometers.

The long-term stability of a well-type chamber can be checked with a source having a long half-life (e.g. caesium-137 or radium-226). The strength, shape and size of the check source are less important in this case. The accuracy is mainly determined by the reproducibility of the positioning of the source and the accuracy of the electrometer. If a considerable change in the (decay-corrected) response is observed, it is recommended to recalibrate the well-type chamber.

Absorption of radiation can heat up the source and its surroundings [24]. This heat is transported to the sensitive volume through conduction and convection, resulting in a thermal gradient. If the sensitive volume is exposed to the atmosphere, the increase of air temperature will result in a decrease of the response of the chamber. It is difficult to correct for this heating because of the temperature gradient. It is recommended to preclude the heating effect; this can be done by shortening the dwell time or by thermally insulating the part of the jig containing the source.

The thickness of the material between the source and the ion-collecting volume must be sufficient to avoid electron contamination.

4. Dose calculations with Iridium-192 sources

4.1 *Air kerma rate and activity*

The reference air kerma rate, $\dot{K}_{ref}$ (in μGy.h^{-1}) is related to the apparent activity, A, of the point source (in MBq) as follows

$$\dot{K}_{ref} = \Gamma_\delta \cdot A$$

with Γ_δ the air kerma rate constant (in μGy.h^{-1}.MBq^{-1}.m^2).
For a source with a reference air kerma rate, $\dot{K}_{ref}$, the air kerma rate at a point P at a distance d (in m) in air, $\dot{K}_{air}(d)$, is given by the inverse square law

$$\dot{K}_{air} = \frac{\dot{K}_{ref}}{d^2}$$

The kerma rate to a small volume of material m -so small that there is no scatter and no attenuation- placed at point P (i.e. the kerma to medium) in air, $\dot{K}_m(d)$, is given by

$$\dot{K}_m(d) = \dot{K}_{air}(d) \cdot (\mu_{tr}/\rho)^m_{air}$$

with $(\mu_{tr}/\rho)^m_{air}$ being the ratio of mass energy-transfer coefficients for the materials m and air.

For a volume of a medium m, large enough to ensure electronic equilibrium, the absorbed dose rate $\dot{D}_{m,air}(d)$, (in μGy.h^{-1}) to the medium in air is given by

$$\dot{D}_{m,air}(d) = \dot{K}_m(d) \cdot (1 - g) =$$

$$= \frac{\dot{K}_{ref} \cdot (\mu_{tr}/\rho)^m_{air} \cdot (1 - g)}{d^2}$$

g is the fraction of the kinetic energy of the secondary particles which is converted to bremstrahlung, in air under calibration conditions; 1-g is taken 1.000 for iridium-192 [20].

If the volume element at point P is not surrounded by air but by the same material m, then absorption and scattering will have to be taken into account. This effect can be described using a function S(d), for which a polynomial expression can be used. Then

$$\dot{D}_{m,m}(d) = \dot{D}_{m,air}(d) \cdot S(d) =$$

$$= \frac{\dot{K}_{ref} \cdot S(d) \cdot (\mu_{tr}/\rho)^{m}_{air} \cdot (1 - g)}{d^2}$$

The use of S(d) and it's parametrization is described elsewhere [13, 16].

4.2 *Relations between quantities and units*

Table 4.1. Relations between quantities and units.

Quantity	*Symbol*	*SI unit*	*Old unit*	*Relation*
Activity	A	Bq	Ci	1 Ci = $3.7 \cdot 10^{10}$ Bq
Dose	D	Gy ≡ J kg^{-1}	rad	1 rad = 10^{-2} Gy
Kerma	K	Gy ≡ J kg^{-1}	-	-
Kerma rate constant	Γ_δ	μGy.h^{-1}.MBq^{-1}.m^2	-	-
Exposure rate constant	Γ_δ^*	pA.kg^{-1}.MBq^{-1}.m^2	R.h^{-1}.Ci^{-1}.m^2	1 R.h^{-1}.Ci^{-1}.m^2 = 1.937 pA.kg^{-1}.MBq^{-1}.m^2

The constants Γ_δ and Γ_δ^* include: gamma radiation, characteristic X-rays and bremstrahlung. The energy of photon radiation is greater than δ keV, where δ is usually taken as 20 keV.

An exposure in air of 1 R corresponds to an air kerma of $2.58 \cdot 10^{-4} \cdot 33.97 \cdot 100 = 0.8764$ cGy (for the ratio of the average energy W to create an ion pair in dry air and the charge e of an electron, the value W/e = 33.97 J.C^{-1} is used, like in previous NCS reports [19, 21]). The bremstrahlung production is assumed to be negligible: 1-g = 1.000.

$$\Gamma_\delta\ (\mu Gy.h^{-1}.MBq^{-1}.m^2) = 0.2369\ \Gamma_\delta^*\ (R.h^{-1}.Ci^{-1}.m^2)$$

As stated in the introduction, the supplier[1] of iridium-192 HDR sources provides at this moment a certificate with the source strength expressed in terms of equivalent activity, deduced from "the measured radiation output of the source". Within the certificate the following correspondence of source strength specifications is used:

A source of 10 Ci ≡ 370 GBq
≡ 4.66 $R.h^{-1}$ at 1 m
≡ 4.0682 $cGy.h^{-1}$ at 1 m

This correspondence is applied in exactly the same way in the case of the Brachytherapy Planning Software[2], which is frequently used in combination with the MicroSelectron-HDR for calculation of dose distributions. So, both certificate and treatment planning software apply a coherent system of source strength specifications, although the conversion factor may differ from what is used in this report.

In order to avoid problems and confusion, it is strongly recommended in this report to measure the source strength in terms of reference air kerma rate in the calibration procedure and to use it in the same units in the treatment planning software and the afterloading equipment.

If a user wants to calculate the source strength in other units for afterloading equipment and/or software, he must use the same conversion factors in the dose calculations and in the software used in the afterloading equipment. It is, however, possible that conversion factors are used in the software that cannot be customized!

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1 Mallinckrodt Diagnostica Holland BV, Petten, The Netherlands

2 Nucletron Trading BV, Veenendaal, The Netherlands

4.3 *Source decay*

Decay of a radioactive source is calculated with

$$A(t) = A(0) \cdot \exp(-\frac{\ln(2) \cdot t}{t_{½}})$$

where $A(t)$ is the source strength at time t, $A(0)$ at time t=0 and $t_{½}$ is the half-life.

Table 4.2. Half-lifes of iridium-192 given in the literature.

Reference	$t_{½}$	
ICRP-38 [11]	74.02	d
NCRP-58 [18]	73.83	d
Browne et al. [2]	74.2	d
Rossiter et al. [26]	73.88	d
Woods et al. [29]	73.83	d
Podgorsak et al. [25]	73.83	d

It is noted here that the value 74.02 d from ICRP-38 [11] is also applied in the decay correction algorithms of the MicroSelectron-HDR and in the Brachytherapy Planning Software[1] and also in the Gammamed-12i[2] afterloading equipment.

Firstly, it is recommended here to use one and the same value of $t_{½}$ in all relevant calculations: i.e. when recalculating the measured source strength to the date of the calibration certificate and when calculating treatment times for future treatments. In practice, the difference between the outcome of calculations with different values of $t_{½}$ is small and can generally be ignored: at 100 days the half-life values quoted by NCRP-58 [18] and Browne et al. [2] result in a difference of only 0.5%.

Furthermore, to improve the overall accuracy of dose calculations, it is recommended to introduce an updated value of 73.83 d of the $t_{½}$ of iridium-192 HDR sources. This however should be accomplished at the same time in all steps of the procedures.

1 Nucletron Trading BV, Veenendaal, The Netherlands

2 Isotopen-Technik Dr. Sauerwein GMBH, Haan/Rheinl., Germany

4.4 *Source anisotropy*

The source strength is specified at a point on the perpendicular bisector of the small cylindrically symmetric source. It has been shown that the actual dose distribution of an iridium HDR source is altered by several per cent compared to the isotropic source model. It is recommended to use a source anisotropy correction factor in the dose calculations in order to have an improved accuracy in the calculation procedures. Knowing the source strength, $\dot{K}_{ref}$, the dose at a point in a medium m, $\dot{D}_{m,m}(d)$, is calculated with the relation

$$\dot{D}_{m,m}(d) = \frac{\dot{K}_{ref} \cdot S(d) \cdot \Phi(\phi) \cdot (\mu_{tr}/\rho)^{m}_{air} \cdot (1 - g)}{d^2}$$

where $\Phi(\phi)$ corrects for the anisotropy of the source as a function of the angle ϕ. In this calculation, it is supposed that the orientation of the source is known, which is generally the case, because the source follows the orientation of the catheter(s). Values of Φ are generally presented in the form of a table as a function ϕ (e.g. [1, 17], for the MicroSelectron-HDR source type[1]).

Values of $\Phi(\phi)$ are explicitly dependent on source construction. Users of iridium-192 HDR afterloading equipment should be aware which source type is present in their machine. The source type may in some cases be recognized from the drive cable coding which is indicated on the source certificate. The appropriate anisotropy correction factors should be used in the treatment planning system. As an example, the anisotropy of the source in the MicroSelectron PDR is markedly different from that of the MicroSelectron-HDR of the same manufacturer[1]. Typical examples of source constructions are shown in figure 4.1.

Manufacturers of sources should clearly state to their users any changes in source construction which may have consequences for the dose calculations.
Publication of relevant data should take place in the open literature and should be supported by the manufacturer.

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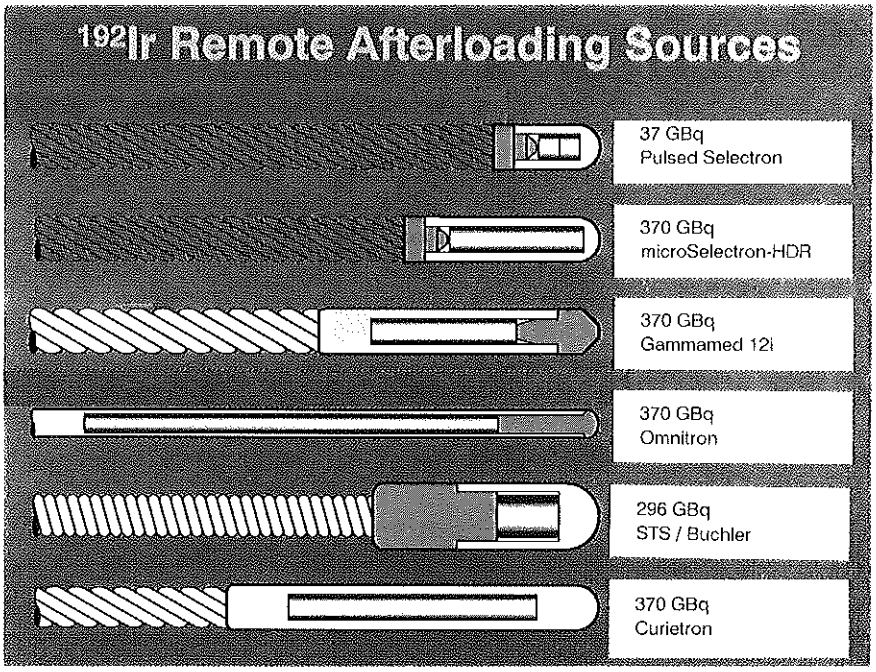

Figure 4.1. *Examples of different types of source construction.*

5. Summary of the recommendations

The uncertainty in the dose specification in HDR brachytherapy (defined as one relative standard deviation) caused by the application of physical procedures should be, if possible, less than 5%. The uncertainty in the calibration of a source itself should be, if possible, less than 2% (1 sd).

The source strength as given on the source certificate from the manufacturer should be verified before patients are treated with the source.

The source strength should be specified in terms of the quantity reference air kerma rate. This quantity is defined as the air kerma rate, in air, at a reference distance of 1 m. It is expressed in the unit $\mu Gy.h^{-1}$.

It is recommended to use the in-air technique, described in section 3.2., as the method of choice for calibration of an iridium-192 HDR source. The other techniques, in-phantom calibration or well-type calibration as described in sections 3.3. and 3.4. respectively, may also be used, but it is mandatory to establish the traceability to the in-air method. For routine use, the value of these two methods is acknowledged.

It is recommended to make use of the calibration services offered by the National Standards Laboratory. A calibration factor for the photon spectrum of iridium-192 can be determined for the reference ionization chamber of the institute. A source calibrated by the National Standards Laboratory can serve as a basis for further measurements by the user, for example in a well-type ionization chamber dedicated for measurements of HDR sources.

It is recommended to determine the strength of each source at least twice: before patients are treated with the source and at the end of the clinical life time of the source. In this way a stability check of the measuring equipment is obtained by the user. The long-term stability of a well-type chamber can also be checked with a source of a long-lived nuclide.

For calculations and/or (computer) planning systems the consistency of the data sets is strongly emphasized. The use of the data as presented in this report is recommended.

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