

**Corrections to Air Kerma Rate
Measurements from a ^{192}Ir High
Dose Rate Brachytherapy Source
to Free Space Conditions**

R.F. Nutbrown and T. Sander

Centre for Ionising Radiation Metrology

AUGUST 2000

August 2000

Corrections to Air Kerma Rate Measurements from a ^{192}Ir High Dose Rate Brachytherapy Source to Free Space Conditions

R.F. Nutbrown and T. Sander
Centre for Ionising Radiation Metrology
National Physical Laboratory
Queens Road
Teddington
Middlesex TW11 0LW
United Kingdom

Abstract. The purpose of this experiment was to determine the combined air scatter and air absorption correction necessary to apply to measurements of the air kerma rate made at a distance of 1 metre from a ^{192}Ir source free in air. This correction needs to be determined as the National Physical Laboratory (NPL) intends to set up a calibration service whereby secondary standard ionisation chambers can be calibrated against a primary standard in terms of air kerma rate at 1 metre in free space from a ^{192}Ir source. Measurements were made with 2 types of chamber. Firstly measurements were made with a 100 cm^3 spherical graphite transfer chamber and then measurements were repeated using a 1.79 cm^3 cylindrical cavity chamber which is one of a set of 3 chambers which form the primary standard for ^{60}Co and ^{137}Cs maintained by the NPL. As both these chambers were originally intended for use with photons of higher energies the graphite caps of the chambers provide a sufficient build up region to develop charged particle equilibrium. The ^{192}Ir source used is a pellet encapsulated in a stainless steel casing, with diameter 1.1 mm and length 5 mm. The source was exposed using a High Dose Rate (HDR) microSelectron brachytherapy unit manufactured by Nucletron. Results from measurements made using the transfer chamber gave an air attenuation correction to be applied to the measured charge at a source to chamber distance of 1 metre of $(1.2 \pm 0.3)\%$. Measurements made using the cylindrical cavity chamber could not be used to determine an estimate of the air attenuation correction for this set up.

© Crown Copyright 2000

Reproduced by permission of the controller of HMSO.

ISSN 1369-6793

National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

Extracts from this report may be reproduced
provided the source is acknowledged
and the extract is not taken out of context.

Approved on behalf of Managing Director, NPL,
by M Sené, Head, Centre for Ionising Radiation Metrology

CONTENTS

1.	Introduction.....	1
2.	Set Up	2
3.	Method	5
4.	Uncertainties	6
5.	Results.....	7
6.	Discussion.....	9
7.	Conclusions.....	10
8.	References.....	12

ILLUSTRATIONS

Figure 1: Plan View of lead castle (not to scale).....	2
Figure 2: Plan View of exposure room (not to scale).....	3
Figure 3: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre. Measurements made using Transfer Chamber for all apertures.....	7
Figure 4: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre. Measurements made using Transfer Chamber for Aperture 1.....	8
Figure 5: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre. Measurements made using Cavity Chamber for all Apertures.....	9

PICTURES

Picture 1: The lead castle that shielded the exposed source.....	4
Picture 2: The transfer chamber mounted on the carriage.....	4
Picture 3: The complete set up	5

1. Introduction

Brachytherapy is the treatment of malignant disease by the interstitial, intracavity or surface application of discrete, sealed radioactive sources. The brachytherapy source is inserted either directly in, or in close proximity to the affected volume thereby only delivering dose to a localised area and so reducing the amount of radiation delivered to healthy tissue.

For brachytherapy purposes an ideal source would comply with all of the following requirements: The half-life of the radionuclide should ideally be long enough to avoid the need for decay corrections to be applied to a treatment plan. A large half-life also reduces the frequency with which source changes must be made which are costly and time consuming. The energy of the radioactive emission would be high enough to reduce unwanted excess energy deposition in bone due to the photoelectric effect and also to reduce scatter. This, however, must be balanced with the increased protection requirements for increasing energy of the emission. The encapsulating material of the source should easily shield any unwanted charged particle emission. The material should be available in an insoluble and non-toxic form that would not disperse if the outer casing were damaged and can be manufactured in a variety of shapes (e.g. wire, pellet). It is also important to account for any daughter products of the radionuclide that should preferably be non-gaseous, insoluble and non-toxic. Radium and radon were used exclusively until the development of nuclear reactors made it possible for other radioisotopes to be manufactured. Radium and radon are now being used far less and have mostly been supplanted with radionuclides such as ^{137}Cs , ^{198}Au , ^{60}Co , ^{125}I and ^{192}Ir .

This investigation uses a brachytherapy unit manufactured by Nucletron which houses a ^{192}Ir pellet shaped source encapsulated within a stainless steel casing. The source, which is attached to the unit by a length of cable, may be programmed to exit the housing and is driven along a narrow plastic tube to a specified point along its length. This tube would be located alongside the malignant tissue and the source programmed to remain at the point of treatment for a specified length of time. Once the treatment is completed the cable is retracted and so returns the source to the housing within the unit. Transition times of the source must necessarily be small in order to reduce transient doses to patients and hospital staff alike.

The National Physical Laboratory (NPL) intends to set up a calibration service whereby secondary standard ionisation chambers can be calibrated against a primary standard in terms of air kerma rate at 1 metre in free space from a ^{192}Ir brachytherapy source of known activity. Knowledge of this quantity is required in order to characterise the source as recommended by the British Committee on Radiation Units and Measurements (BCRU)¹. In order to determine the absolute air kerma rate at 1 metre in free space measurements must be directly traceable to an established primary standard. A cavity chamber originally designed for use with photons generated with a Van de Graaff generator at an energy of 2 MV was selected as the most suitable primary standard that is established at present at the NPL. This chamber has a volume of 1.79 cm³. Measurements were also made with a protection level spherical transfer chamber with a volume of 100 cm³.

The purpose of this investigation is to determine the combined air scatter and air absorption correction necessary to apply to measurements of the air kerma rate at 1 metre that account for the fact that measurements are made in air and not in free space. In order to determine the total air attenuation correction it was necessary to vary the radiation field size at the point of measurement. As extra shielding was required around the source in order to avoid a scatter contribution from the walls of the exposure room the source was shielded inside a lead castle with the option of slotting various sized conical apertures into the front face. Measurements were made with each chamber for 4 different sized apertures at different source to chamber

distances. The air attenuation correction was then determined empirically and compared with the total measured air attenuation correction.

2. Set Up

A lead castle was constructed of wall thickness 5 cm (see Picture 1) around the point at which the brachytherapy source was to be exposed. Four conical apertures of different sizes were manufactured which could fit into the front face of the lead castle. The bore diameters of Apertures 1 to 4 were 15, 25, 35 and 50 mm respectively. A hole was drilled through one of the lead bricks that was used to make up one of the sidewalls of the lead castle. The plastic tube through which the source is driven was passed through the hole in the sidewall and secured on the inside face of the opposite wall (see Figure 1).

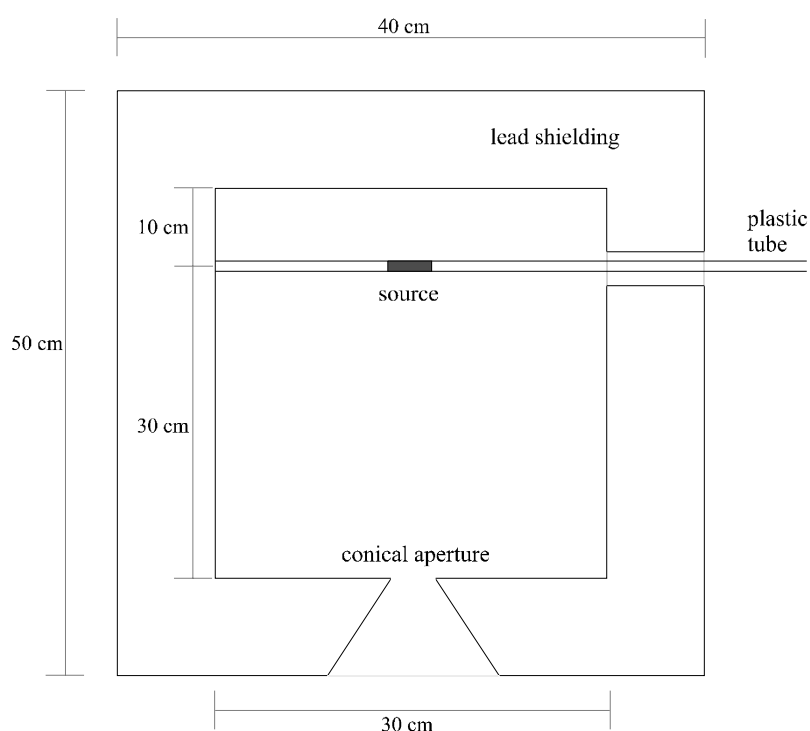


Figure 1: Plan View of lead castle (not to scale)

A light source was placed inside the lead castle in order to assist in aligning the source. A cross was painted on the back wall of the lead castle that was coincident with the centre of the conical aperture in the front face of the castle. This was used as a marker for aligning the position of the source. A telescope, mounted at the far end of the room, was used to ensure that the centres of the ionisation chamber, the aperture, the plastic tube and the cross marking the position of the centre of the source were aligned. The ionisation chambers were mounted on a carriage that could be moved sideways so that either chamber could be positioned in the beam (see Figure 2 and Pictures 2 and 3). The carriage could also be moved along the length of the room so that measurements could be made at different distances from the source.

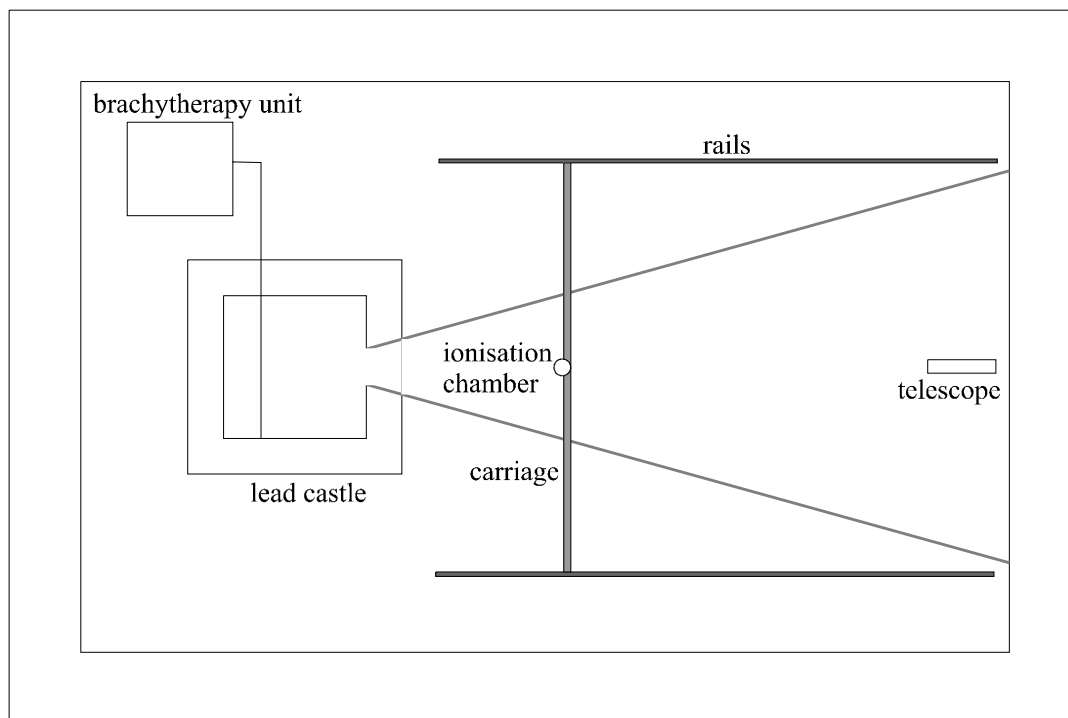
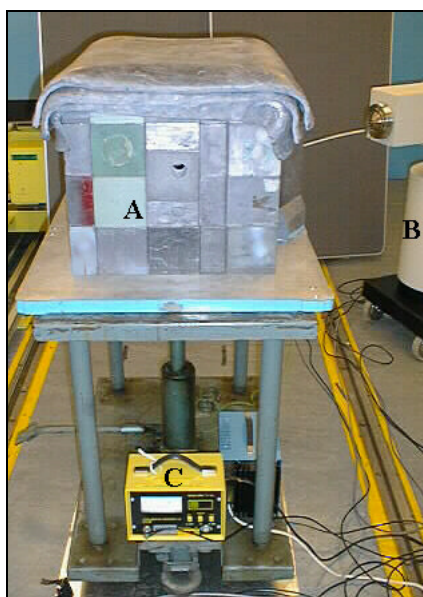


Figure 2: Plan View of exposure room (not to scale)

In order to prevent accidental exposure the design of the brachytherapy unit (see Picture 3) is such that it must be used in a room with an interlock system. The unit has a real source and a dummy source that is used to test that there are no obstructions such as kinks in the tube. Neither source can be exposed unless the interlock system is closed. Therefore, in order to determine the distance along the tube at which the source is aligned a television camera was positioned facing down the aperture while the dummy source was exposed. The position was varied until the source was aligned and the camera was then removed. When measurements were made using the real source this predetermined position was programmed into the brachytherapy unit.

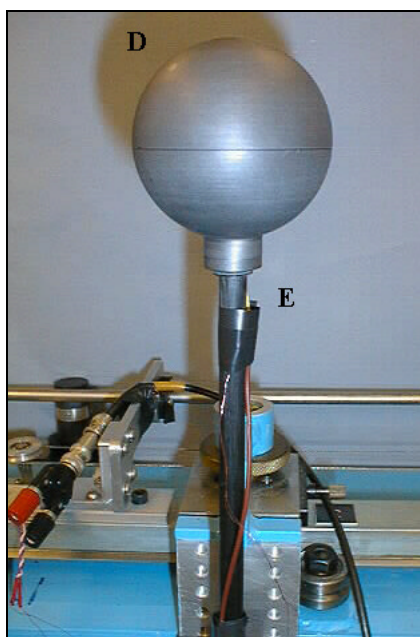
The dosimeter used to make measurements of the collected charge was a Dosemaster Type 2590B (serial number 132) manufactured by NE Technology that was calibrated at the National Physical Laboratory. Leakage currents from the ionisation chambers were also measured using the dosimeter. This current was minimised by delivering a pre-measurement dose to the chambers at the start of each day of measurements.

The experimental set up was designed so that the scatter contribution measured by the ionisation chambers was minimised. The source was positioned 10 cm from the back wall of the lead castle in order to reduce the amount of backscattered radiation escaping through the conical aperture. Scatter from the sidewalls of the castle escaping through the aperture was also kept to a minimum by ensuring that the dimensions of the lead castle were as large as possible. Limits on the size were determined by weight and the practicality of the construction and set up. The maximum size of the conical aperture was restricted so that the direct path of the radiation did not impinge on the sidewalls, ceiling or floor of the room in which the measurements were carried out. This meant that only scatter from the back wall of the room contributed to the measured ionisation current. By making measurements at large distances from the back wall (typically at least 4 m) this scatter contribution was minimised. Dimensions of the conical apertures were calculated so as to reduce scatter from the mouth of the aperture.



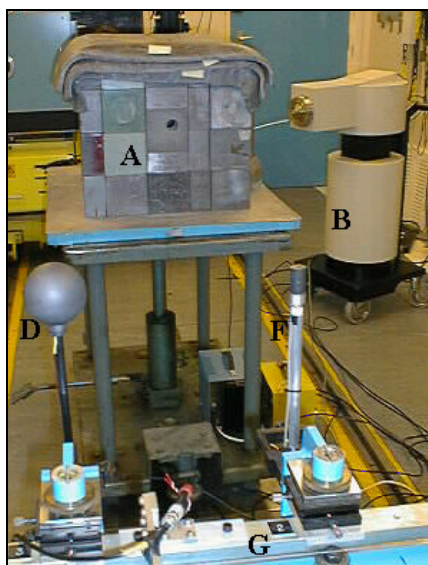
Picture 1: The lead castle that shielded the exposed source

Picture 1 The lead castle (A) that was constructed to shield the exposed source. The tube from the brachytherapy unit (B) was passed through a hole drilled through one of the lead bricks of the sidewall. The tube was then attached to the inside of the opposite wall. A gamma alarm (C) was used as part of the safety procedure to indicate when the ^{192}Ir source was exposed.



Picture 2: The transfer chamber mounted on the carriage

Picture 2 The spherical transfer chamber (D) mounted on the carriage prior to measurement. The chamber is positioned in the centre of the beam using a telescope that is mounted at one end of the exposure room. Attached to the stem of the chamber is a calibrated thermistor (E) that is taped to the stem so that it is in contact with the chamber. Temperature and pressure readings were made in order to correct measurements made of the collected charge.



Picture 3 The complete set up:

A = lead castle
 B = brachytherapy unit
 D = transfer chamber
 F = cavity chamber
 G = carriage

The mounting on the carriage can be moved across so that either chamber can be positioned in the beam. The carriage itself can be moved along the length of the room so that measurements can be made at varying source to chamber distances.

Picture 3: The complete set up

3. Method

Initially measurements were made of the leakage current from the spherical transfer chamber and the cylindrical cavity chamber. A pre-measurement dose of at least 1 Gy was delivered to both the chambers. This was done to eliminate any charge that may have built up on the insulator while the chamber was not in use. This is a standard procedure at NPL and measurements made during this investigation showed that pre-irradiating the chambers reduced the leakage currents significantly. The pre-measurement irradiation was carried out using an X-ray tube as much higher dose rates could be delivered compared to the dose rate delivered by the ^{192}Ir source. The leakage current from the transfer chamber was found to be negligible, however, the leakage current from the cavity chamber was found to be of the order 5×10^{-15} A. Therefore, in order to ensure that the leakage current from the cavity chamber was less than 1% of the measured current the minimum ionisation current should be at least 5×10^{-13} A.

Firstly measurements were made using the spherical transfer chamber at various source to chamber distances between 85 cm and 385 cm. Under these conditions ionisation currents of between 4×10^{-11} A and 2×10^{-12} A were measured. Measurements were made of the time taken to collect between 5×10^{-9} C of charge at 85 cm and 2×10^{-10} C of charge at 385 cm. This allowed a set of 5 measurements to be done in the maximum irradiation time of 999 s allowed by the programming of the Nucletron microSelectron. It was not necessary to apply a decay correction to this set of measurements as the decay correction in this time is only of the order 0.01%. For each distance 2 sets of independent measurements were made to check repeatability and to enable a spread to be determined. Measurements were then made using the cylindrical cavity chamber at various source to chamber distances between 60 cm and 80 cm. Under these conditions ionisation currents of between 1×10^{-12} A and 7×10^{-13} A were measured and, as previously, 2 sets of 5 measurements were made. This procedure was repeated for each of the 4 apertures.

During each measurement, readings of the temperature and pressure were recorded which allowed the measurements to be corrected to a standard temperature and pressure (20 °C and

1013.25 mbar). The time at which each measurement was made was also recorded so that a decay correction could be applied to a reference time and date of 00.00 hours on 1st January 1999. Range and scale correction factors that were supplied with the calibration of the dosimeter were also applied as measurements were made on different ranges and to different points of the scale. Measurements were also corrected for the inverse square law to give ionisation current at 1 metre in air.

Therefore the ionisation current at the reference time for standard conditions corrected to 1 metre, I_{ref} , is given by:

$$I_{ref} = I_{measured} \cdot \exp(\lambda t) \cdot k_{STP} \cdot k_{SC} \cdot k_{RC} \cdot d^2$$

Where:

$I_{measured}$	is the measured ionisation current,
t	is the time difference between the measurement and reference time,
λ	is given by $\frac{\ln 2}{\tau}$ where τ is the half-life of ^{192}Ir and is equal to 73.8 days ² ,
k_{STP}	is the temperature and pressure correction,
k_{SC}	is the scale correction factor for the dosimeter,
k_{RC}	is the range correction factor for the dosimeter,
d	is the source to chamber distance.

4. Uncertainties

All error bars shown for the plots given in Section 5 are the maximum spread observed ($\pm 0.3\%$) on any two sets of measurements. This was assumed to be a reasonable estimate of the type A uncertainty associated with the measurements; however, there is also a type B uncertainty that has not been accounted for. For each sized aperture, measurements were made with the spherical transfer chamber and then the cavity chamber. In order to change the aperture it was necessary to remove the lead sheets that comprised the roof of the lead castle, which meant that the whole set up required re-aligning. Also, all of the source to chamber distances required checking and re-marking, therefore, there will be a small uncertainty in the source to chamber distance of the order ± 1 mm. As can be seen from Figure 3, and discussed in Sections 5 and 6, the results using different apertures show good agreement within the type A uncertainty shown. Due to time restrictions it was not possible to repeat any measurements after changing the aperture in order to determine the size of this type B uncertainty, however, it has been assumed to be negligible compared to the type A uncertainty. Therefore the total uncertainty at 1σ is determined to be 0.3%.

5. Results

The results obtained from measurements made with the spherical transfer chamber showed a decrease in the ionisation current corrected to 1 metre with increasing source to chamber distance (see Figure 3). The increasing air absorption and air scatter out of the beam that would give a lower ionisation current within the chamber with increasing distance can explain this.

Good agreement was found between measurements made with different sized apertures at small source to chamber distances (excepting one spurious result which will be discussed in Section 6); however, at larger distances the readings begin to diverge. This effect, which increases with increasing distance, gives a greater ionisation current with increasing aperture diameter. This is explained by considering the radiation that is scattered back towards the chamber by the surrounding air. The increased field size produced by the larger apertures increases the scattered radiation. It can be seen from Figure 3 that this effect is most pronounced when measurements are made using the largest aperture at the greatest source to chamber distance. Therefore, in order to minimise this air scatter contribution and remove the need to apply a correction for this, measurements should be made using an aperture that reduces the beam size at the point of measurement such that the sensitive volume of the ionisation chamber is just covered.

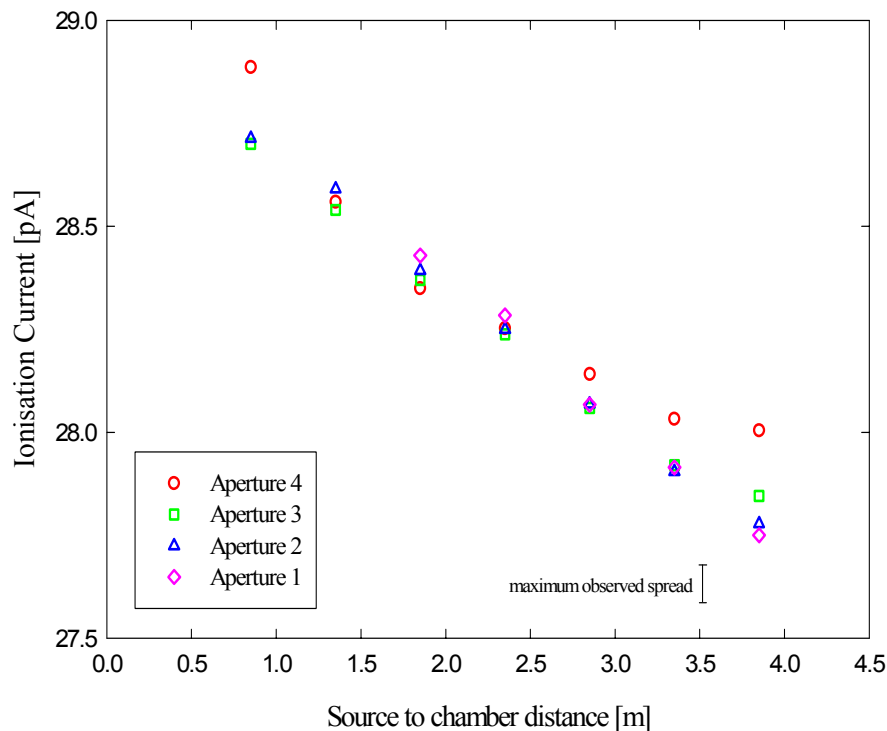


Figure 3: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre. Measurements made using Transfer Chamber for all apertures.

By using the results obtained from measurements made using Aperture 1 it is possible, therefore, to obtain a combined air absorption and air scatter correction that has a linear relationship with source to chamber distance, see Figure 4. The air scatter correction should be mainly due to photons that are scattered out of the direct beam as the contribution from scatter into the direct beam has been minimised by using the smallest aperture.

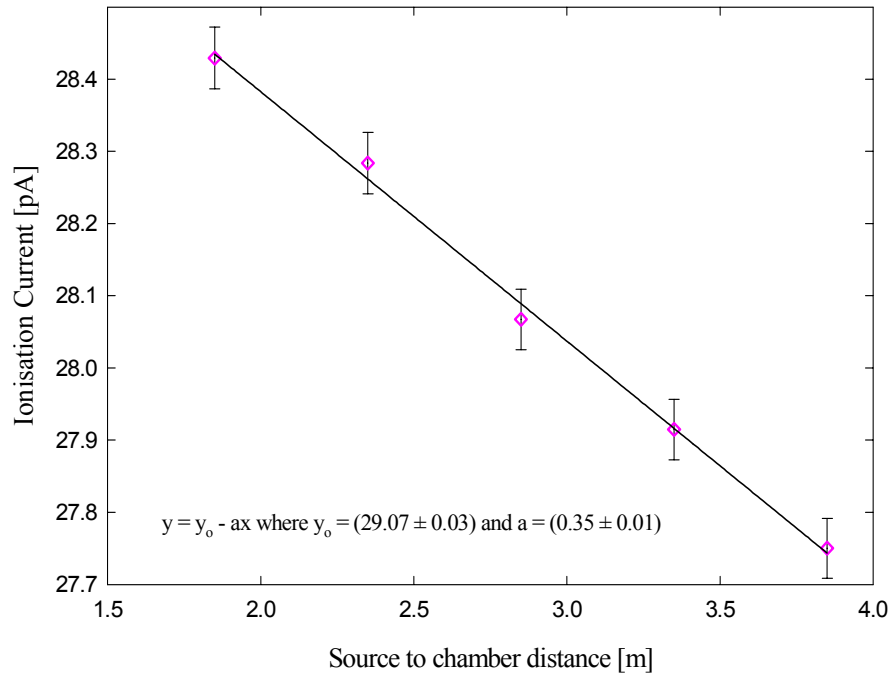


Figure 4: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre.
Measurements made using Transfer Chamber for Aperture 1.

From Figure 4 it can be seen that the correction, which would need to be applied to the ionisation current to account for the air absorption and air scatter out of the beam, must be greater than unity as the attenuation by the air tends to reduce the ionisation current, I_{ion} . Therefore, the correction to apply to the ionisation current is given by:

$$\frac{I_{ion}(0\text{ m})}{I_{ion}(1\text{ m})}$$

From Figure 4 it can be seen that the line of best fit lies within the maximum observed spread of the measurements and gives:

$$\begin{aligned} I_{ion}(0\text{ m}) &= (29.07 \pm 0.03) \text{ pA} \\ I_{ion}(1\text{ m}) &= (28.72 \pm 0.04) \text{ pA} \end{aligned}$$

Therefore, the air absorption and air scatter correction that must be applied to measurements of ionisation current made using the spherical transfer chamber at a distance of 1 metre from the source correct to a measurement in free space is:

$$(1.2 \pm 0.3)\%$$

An estimate of the total narrow beam air attenuation correction (to first order only) can also be calculated separately as:

$$k_{air\text{ attenuation}} = \exp(\mu d)$$

Where:

μ is the total narrow beam attenuation coefficient for air,

d is the source to chamber distance.

Values of the total attenuation coefficient in air, μ , and the partial interaction coefficients in air were calculated for the photon energies that make up the ^{192}Ir energy spectrum using the computer program XCOM³. These calculated values were used to determine a weighted average value for μ of $9.11 \times 10^{-5} \text{ cm}^{-1}$. This gives a total air attenuation correction of 0.9% at 1 metre from the source. Therefore the measured and empirically determined air attenuation corrections show good agreement. Values of the partial interaction coefficients in air also showed that this total attenuation correction is almost completely dominated by incoherent scattering with a negligible contribution due to coherent scattering and photoelectric absorption.

Figure 5 shows the results for measurements made using the cylindrical cavity chamber. The results show the same general trend as the previous results from the transfer chamber of a decrease in the ionisation current with increasing source to chamber distance. However, due to the large spread in results for the different apertures it is not possible to determine the combined air absorption and air scatter correction for the different aperture sizes with a satisfactory uncertainty.

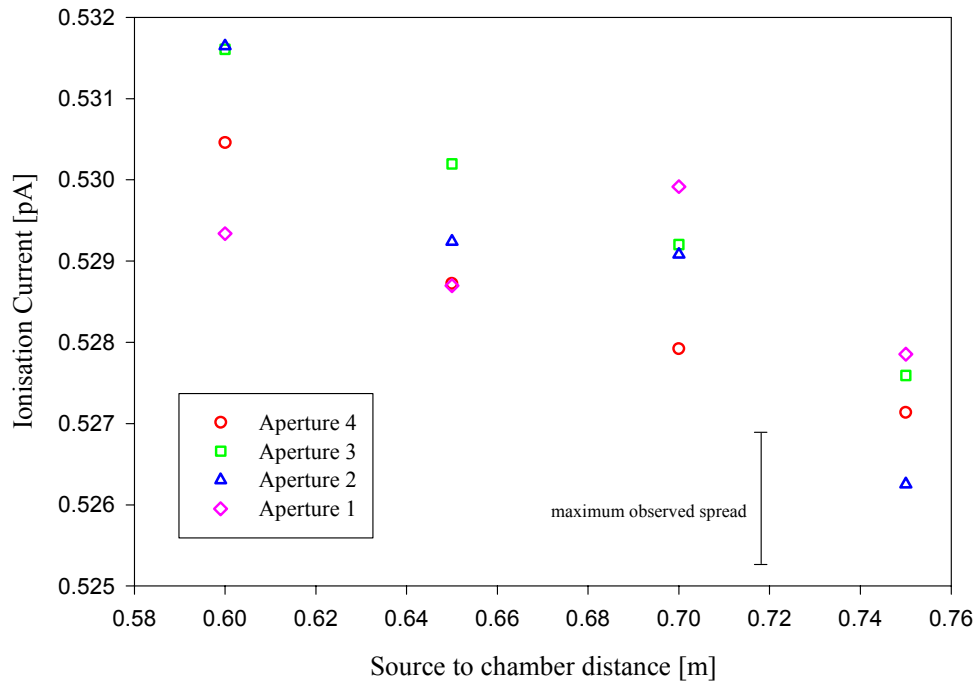


Figure 5: Variation of Ionisation Current with Source to Chamber Distance normalised to 1 metre. Measurements made using Cavity Chamber for all Apertures.

6. Discussion

From Figure 3 it can be seen that all of the results for measurements made using the transfer chamber with different sized apertures follow the same trend as explained previously in Section 5 except for the measurement made at the closest distance with the largest aperture, Aperture 4. This point lies above where it would be expected to lie, i.e. the ionisation current is greater than expected. This can be explained by an increase of scattered radiation produced at the mouth of the aperture. Increasing the aperture diameter increases the surface area. As the number of scattering centres is directly proportional to the surface area, using a large

aperture will lead to an increase in the collected ionisation current. Scattered radiation is also produced within the lead castle. The amount of scattered radiation that escapes through the aperture would be more significant for larger aperture diameters. Both of these effects would be greatest at the smallest source to chamber distances. However, at the closest distance, the point for Aperture 3 lies below the point for Aperture 2, which is not expected as Aperture 3 is larger than Aperture 2 and so there should be more scattered radiation reaching the point of measurement. The random scatter in the points can explain this.

It has been assumed that the increase in the ionisation current normalised to 1 metre with increasing aperture diameter at larger distances is solely due to scatter from the surrounding air. However, when the beam size at the point of measurement is large the beam is likely to impinge on the carriage on which the chambers are mounted. Therefore scatter from the carriage itself may contribute to the collected charge. This problem is eliminated, however, if the aperture size is restricted.

Measurements made using the cylindrical cavity chamber showed the same general trend that was observed when using the spherical transfer chamber. The maximum observed spread on a repeated set of measurements was 0.3% for both chambers. There was, however, a much larger spread in the results for different apertures when using the cylindrical cavity chamber. This spread displayed no observable trend with increasing aperture diameter. This meant that it was not possible to determine a reasonable estimate of the correction. The large spread in the results may be due to the fact that measurements were made at much closer distances to the aperture than when using the transfer chamber to enable larger ionisation currents to be measured. This makes it more likely that scatter from the aperture or from inside the lead castle will have made a significant contribution to the measured ionisation current.

All measurements made of the air kerma rate at 1 metre in air require a correction to be applied to the source to chamber distance to account for the finite size of the chamber. The chamber having a finite size means that the effective point of measurement is likely to be closer to the source than the geometric centre of the chamber. See Reference 4 for further details of this correction for a spherical detector. This correction can be seen to be negligible for measurements made using the spherical transfer chamber (of the order 0.1 mm). This correction can be approximated for the cylindrical cavity chamber and is found to be approximately an order of magnitude smaller and so is therefore also negligible.

7. Conclusions

Measurements of the air kerma rate from a high dose rate ^{192}Ir brachytherapy source made using the spherical transfer chamber showed good repeatability. By using an aperture that restricts the beam size it was possible to determine an air attenuation correction that has a linear relationship with source to chamber distance. It should be noted that the air attenuation of the ionisation current would be expected to display an exponential relationship with source to chamber distance; however, over this range a linear relationship gives a good approximation. The value of this correction, which must be applied to measurements of ionisation current at a distance of 1 metre from the source, is $(1.2 \pm 0.3)\%$ and is wholly due to air scatter out of the beam. However, when using the smallest aperture the transfer chamber was not completely irradiated by the beam at the two smallest source to chamber distances. Therefore, an optimum size of aperture would allow measurements to be made at the desired source to chamber distance whilst still restricting the beam size sufficiently at the point of measurement. The spherical transfer chamber is a suitable choice for making measurements of air kerma from the high dose rate ^{192}Ir brachytherapy source as it has a large

volume and a small leakage current. However, as this chamber is not an established primary standard the use of this chamber alone is not sufficient to set up a calibration service.

The main problem identified with using the current NPL primary standard cavity chamber for the measurements of the air kerma rate from a ^{192}Ir source is its size, which restricts the amount of charge that can be collected. This problem combined with the large leakage current compared to measured ionisation current means that it is necessary to make measurements close to the mouth of the aperture. This may introduce an additional problem in that there is likely to be increased scatter from the mouth of the conical aperture at small distances. These reasons make the cavity chamber unsuitable for these measurements.

Therefore, in conclusion, further work needs to be carried out to either establish a new, more suitable primary standard or, to characterise the response of the transfer chamber with respect to the cavity chamber at the different energies that make up the ^{192}Ir spectrum. In this case the air attenuation correction determined in this work can be used to correct measurements made using the transfer chamber to free space conditions.

8. References

- 1 BCRU (British Committee on Radiation Units and Measurements), *Specification of brachytherapy sources*, Br J. Radiol. **57**, 941-942, (1984)
- 2 Kaye, G.W.C. and Laby, T.H., *Tables of Physical and Chemical Constants*, ISBN-0-582-22629-5, 16th edition (1995)
- 3 Berger, M.J. and Hubbell, J.H., *XCOM: Photon cross sections on a personal computer*, Report NBSIR 87-3597, National Bureau of Standards, Gaithersburg, MD 20899, (1987)
- 4 Shipley, D.R. and Duane, S., *Corrections to air kerma rate measurements of ^{125}I brachytherapy sources to free space conditions*, NPL Report RSA(EXT) 51, (1994)