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ABSTRACT

Two Fricke-based absorbed dose to water standards for HDR Ir-192 dosimetry, developed independently by the LCR in Brazil and the NRC in Canada have been compared. The agreement in the determination of the dose rate from a HDR Ir-192 source at 1 cm in a water phantom was found to be within the k=1 combined measurement uncertainties of the two standards: D_{NRC}/D_{LCR} = 1.011, standard uncertainty = 2.2 %. The dose-based standards also agreed within the uncertainties with the manufacturer's stated dose rate value, which is traceable to a national standard of air kerma. A number of possible influence quantities were investigated, including the specific method for producing the ferrous-sulphate Fricke solution, the geometry of the holder, and the Monte Carlo code used to determine correction factors. The comparison highlighted the lack of data on the determination of $G(Fe^{3+})$ in this energy range and the possibilities for further development of the holders used to contain the Fricke solution. The comparison also confirmed the suitability of Fricke dosimetry for Ir-192 primary standard dose rate determinations at therapy dose levels.

Keywords: Fricke dosimetry, Ir-192 HDR brachytherapy, absorbed dose standards.

1. Introduction

High Dose Rate Brachytherapy (HDR-BT) is a non-permanent type of brachytherapy in which the high activity source is placed near the tumour during treatment (Skowronek, 2013; Yoshioka, 2013). Although a number of isotopes have been investigated, Ir-192 is the one most commonly used in clinical practice because of its high specific activity and desirable mean photon energy around 400 keV (Nikoofar, 2015).

One of the challenges associated with the use of Ir-192 sources is related to its absolute calibration. The emission spectrum of the source, which is complicated by the additional contribution of the source encapsulation and not-insignificant scatter effects, makes modelling of its dosimetry difficult (Ferreira *et al*, 1999; Stump *et al*, 2002; Marechal *et al*, 2002; Marechal *et al*, 2003). Ir-192 absorbed dose to water has historically been traceable to air kerma standards (Di Prinzio and de Almeida, 2009), e.g. via the AAPM TG-43 formalis (Nath *et al*, 1995, Rivard *et al*, 2004) with secondary systems such as TLD or radiochromic film used to confirm the conversion from kerma to dose (Lucas *et al*, 2014). The Bureau International des Poids et Mesures (BIPM) has initiated an international comparison of Ir-192 HDR air kerma standards (e.g. Kessler et al, 2016) and in recent years a number of institutions have developed calorimeter-based absorbed dose standards for Ir-192 (Sarfhenia and Seuntjens, 2010; Selbach *et al*, 2012; Sander *et al*, 2012).

The National Research Council Canada (NRC), in Ottawa, Canada, and the Radiological Science Laboratory (LCR), in Rio de Janeiro, Brazil, have studied the use of Fricke dosimetry as a possible method to obtain a primary standard of the absorbed dose to water for Ir-192 sources (Franco *et al*, 2011; de Almeida *et al*, 2014; El Gamal *et al*, 2015). There are some important differences in the approach taken by each group, including preparation of the Fricke solution, the irradiation geometry (specifically the holder for the solution) and the Monte Carlo code used to derive the necessary correction factors. It is therefore worthwhile to compare the standards to investigate possible systematic effects in either methodology.

Although Fricke dosimeters have been successfully used in mailed dosimetry services, both at therapy and industrial dose levels, the standard glass or quartz ampoules used

for such services (typically for Co-60 measurements) are not suitable for the lower photon energy of Ir-192. Also, the use of a transfer dosimeter introduces an extra uncertainty due to the transport process. Therefore all the measurements reported here were performed at the Ionizing Radiation Standards laboratory of the NRC by researchers from both the LCR and NRC. The advantage of this approach is that it removes any dependence of the specific Ir-192 irradiator used by each group. The disadvantage is that there is a stronger correlation between the measurements, e.g., because the same read-out system (spectrophotometer) is used.

It is worth summarizing what is being compared:

i) Formulation of Fricke solution (each lab prepares the solution to their standard 'recipe')

ii) Irradiation geometry (each lab uses a different holder to irradiate the Fricke solution with the same Ir-192 source)

iii) Correction factors (each lab uses their own Monte Carlo software to evaluate the necessary correction factors). NRC uses the EGSnrc system, while LCR uses the PENELOPE code.

Also, the comment elements are:

a) Same chemical reagents for preparation of Fricke solutions.

b) Same spectrophotometer for read-out of Fricke solutions.

c) Same Ir-192 source for irradiations.

Since the NRC methodology has already been presented in the literature (McEwen *et al*, 2014; El Gamal *et al*, 2015), the text below focusses on the LCR procedures and measurements.

2. Methodology

The NRC measurements (i.e., preparation of the solution, irradiation of samples, read-out, analysis, and Monte-Carlo simulation), were completed immediately prior to the LCR measurements at NRC. In this and following sections, we describe the steps required to determine absorbed dose to water for Ir-192 and highlight the differences among the NRC and LCR methodologies.

2.1 Absorbed Dose to Fricke Determination

The absorbed dose to the Fricke solution was determined by both groups using the following expression:

$$D_F = \frac{\Delta OD}{G(Fe^{3+})\cdot L\cdot \rho\cdot \varepsilon} \quad (1)$$

where,

ΔOD is the absorbance difference between the irradiated solution and a non-irradiated control sample;

G (Fe^{3+}) is the radiation chemical yield for ferric irons for the specific radiation beam/source;

L is the optical path length of the cuvette, which in this case was 1.000 ± 0.002 cm

ρ is the Fricke solution density, which in the literature is 1.024 g/cm^3 at 25 °C;

ε is the molar linear absorption coefficient of the ferric ions, with a value of 2174 × 10^3 cm^2 mol^{-1} at 304 nm (Cottens *et al*, 1981).

As the irradiation and readout temperatures are very important for the determination of both ε and G (Fe^{3+}), the ΔOD was corrected using the following expression (taken from Olszanski *et al*, 2002):

$$\Delta OD = (OD_i - OD_c) \cdot [1 + 0.0012 \cdot (25 - T_i)] \cdot [1 + 0.0069 \cdot (25 - T_r)] \quad (2)$$

where,

OD_i is the absorbance of the irradiated solution;

OD_c is the absorbance of the control solution;

T_i is the temperature in °C of the Fricke solution during irradiation; and

T_r is the temperature in °C of the Fricke solution during the spectrophotometer reading.

2.2 Preparation of the Fricke solution

a) **LCR** – the laboratory glassware was first cleaned with 5 % diluted Extran (MERCK-KGaA, Darmstadt, Germany), rinsed at least 10 times, and then filled with sulfuric acid 96 %, which remained in the glassware for at least 24 h. After this period, the glassware was rinsed at least 10 times and then dried in an oven.

The Fricke solution was prepared in a 1-L volumetric flask. First, 22 ml of sulfuric acid, 98 % (MERCK-KGaA, Darmstadt, Germany), was diluted with 250 ml of high purity water (at NRC this is from a Millipore Milli-Q system). The water-acid mixture was pre-irradiated with 10 Gy, using a Co-60 unit. After 1 h, 0.06 g of sodium chloride (MERCK-KGaA, Darmstadt, Germany) and 0.392 g of ammonium iron (II) sulphatehexahydrate (MERCK-KGaA, Darmstadt, Germany) were added. A final volume of 1 L was achieved with high purity water, using the scale of the volumetric flask. The flask containing the Fricke solution was sealed and stored away from any light sources for 24 h before use.

b) **NRC** – the NRC system has been described in detail by Olszanski *et al* (2012), Cojocaru *et al* (2012) and El Gamal (2013). It is sufficient here to state that the basic procedure is similar to that of the LCR.

2.3 Holder for Fricke solution

a) **LCR** – a PMMA (polymethylmethacralate) holder was carefully designed and is shown in Figure 1. It allows the centre of the source inside the catheter to coincide with the geometric centre of the ring, which is filled with the Fricke solution. The irradiated solution volume was 18.4 cm^3, which was sufficient to fill two spectrophotometer cuvettes and obtain two readings for each irradiation.

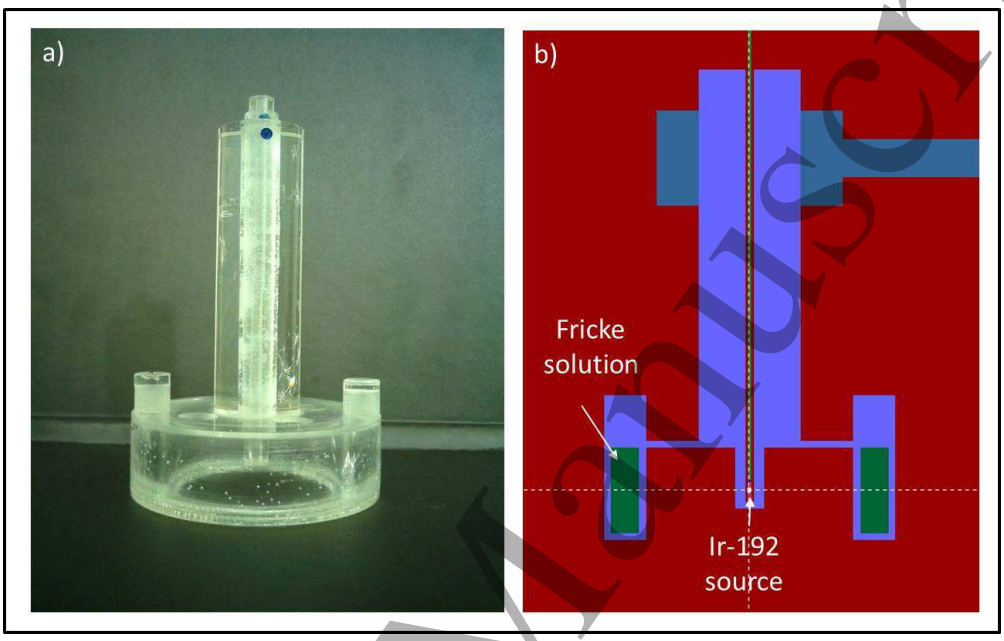

Figure 1. Irradiation vessel developed at the LCR: a) picture of the holder; b) schematic view as modelled using the PENELOPE Monte Carlo code.

b) **NRC** – the NRC holder has been described in detail by El Gamal *et al* (2015). A schematic is shown in Figure 2. The main differences between the NRC and LCR holders are the reference position, the volume of Fricke irradiated and the mass of non-water material. The NRC design of the holder allows the dose rate to be measured at 1 cm, which is the distance recommended by the AAPM TG 43 protocol (Nath *et al*, 1995), but the constraint of measuring close to the source means that there is limited Fricke solution available for readout. This means that smaller cuvettes (optical pathlength = 1 cm) and more irradiations are required compared to the LCR geometry to obtain a suitable number of spectrophotometer readings.

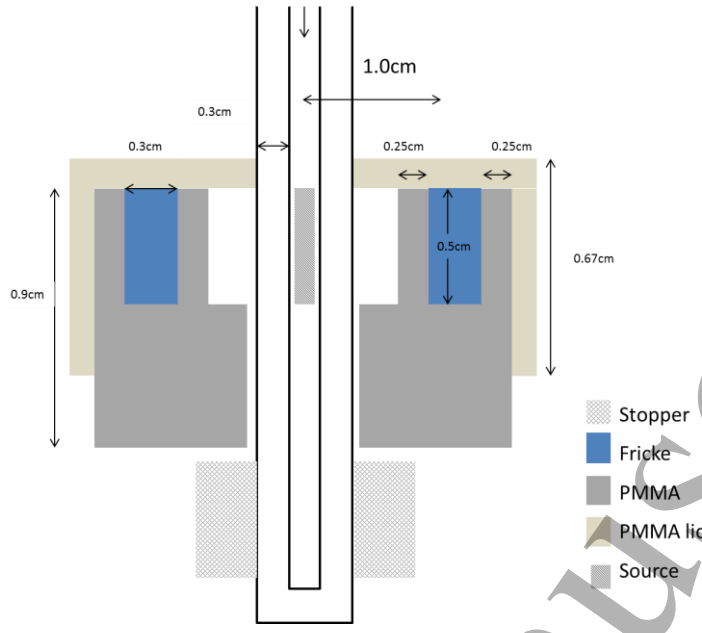

Figure 2. Fricke holder cross-section (not to scale). Blue regions represent Fricke solution. The Ir-192 source is shown as the shaded rectangle in the middle of the guide tube. For the Monte Carlo simulations, all unshaded components were modeled as water.

3. Irradiation

A Nucletron microselectron afterloader was used with a microselectron V2 Ir-192 source. The position of the source was determined with a resolution of ± 0.1 mm using a diode detector, as described in El Gamal *et al* (2015). This process was repeated at the beginning of each day's irradiations to take account of any possible variations in the afterloader positioning.

a) **LCR** - the irradiations were performed for a period of 990 seconds. Two different cuvettes, denoted cuvette A1 and A2, were filled with Fricke solution from one irradiation and were read using an NRC-modified Cary 400 Scan spectrophotometer. This can read two cuvettes simultaneously, along with a standard absorbance filter and an empty optical path. Compressed nitrogen is continually blown through the readout compartment while the readings are taken to prevent dust from accumulating on the cuvette surfaces. An in-house control system ensures that the sample holder is at 25 °C

before any readings are taken. The program reads each sample 4 times, and each reading is an average of 5 measurements. See Olszanski *et al* (2002) for a full description of the modifications.

Before each set of irradiations, the cuvettes were rinsed 3 times, filled with high purity water, and then the absorbance was read to confirm no contamination. If the optical absorbance reading, at 303 nm, was 0.0362 or less, then the cuvettes were considered clean. Otherwise, they were cleaned again using cotton swabs, acetone and high-purity water from the Milli-Q system, until the spectrophotometer reading was at the required level.

Each day, before the first and after the final irradiation, controls were prepared. The Fricke solution remained in the holder for the same period as for the irradiations (~ 990 s).

b) **NRC** – the irradiation procedure has been documented (El Gamal, 2013; El Gamal *et al*, 2015). The process is very similar to that described for the LCR irradiations.

4. Determination of G(Fe^{3+})

The G-value is the constant that links the energy deposited in the Fricke solution with the number the ferric ions produced. The G-value can be determined by inverting equation (1):

$$[G(Fe^{3+})\cdot L\cdot \rho\cdot \varepsilon] = \frac{\Delta OD}{D_F} \qquad (3)$$

Since it is not possible to determine the G-value through theoretical means it must be determined experimentally and equation (3) shows that one needs an independent measure of the absorbed dose to Fricke. This would appear to negate Fricke as the basis of a primary standard. Klassen *et al* (1999) provide a detailed review of historical G-value determinations at various photon energies and suggest, at least for Co-60, that G(Fe^{3+}) can be viewed as a "constant" similar in concept to the parameter W_{air} in air kerma standards. More recently the ICRU have considered the issue of the universality of the

G-value (ICRU, 2016). Unfortunately, Klassen *et al* also show that the G-value data in the energy range for Ir-192 is quite old, dating from the 1960s (Fregene, 1966) and with large uncertainties. To address this problem, McEwen *et al* (2014) applied an approach previously used for Ir-192 air kerma determination (Goetsch *et al*, 1991) – interpolation of data obtained at Co-60 and kV x-ray energies. The technique relies on accurate dose determination in the two reference beams to give $G(Fe^{3+})$ for Co-60 and 250 kV x-rays and McEwen *et al* (2014) report a standard uncertainty (k=1) in the G-value for Ir-192 of 0.6 % (for the standard NRC Fricke solution).

As part of this comparison it was not possible to independently verify this new value for $G(Fe^{3+})$ but the NRC measurements were repeated using the LCR Fricke solution. This investigation only tests whether there is any sensitivity to the specific Fricke solution.

4.1 Preparation of the plastic bags

A crucial feature of the NRC methodology is that the Fricke solution is irradiated in thin polyethylene (PE) bags, essentially creating a wall-less volume. This method was pioneered by the Swiss national metrology institute, METAS (Stucki and Vörös, 2007) and has also been used at NRC for dose measurements in MeV electron beams (Cojocaru *et al*, 2012). Contamination of the Fricke solution by material leaching from the PE bags is a major concern and therefore a rigorous cleaning procedure was adopted.

The bags were cut from a plastic roll and then closed at the bottom using a heat sealer. The bags were then cleaned 10 times on both sides with high-purity water and dried with nitrogen gas. The bag was then filled with LCR Fricke solution, with a target weight of 4.25 ± 0.03 g. The bags were sealed two times using the heat sealer and positioned in a PMMA irradiation holder consisting of 1 mm thick plates front and back (see McEwen *et al*, 2014). The bag adopts an approximately rectangular shape, 30 mm × 30 mm × 3 mm, constrained by the PMMA walls of the holder (see Stucki and Vörös, 2007). After irradiation, the bags were cleaned 10 times on the outside with high-purity water and then dried with nitrogen before being opened with cleaned, ceramic scissors. The solution was removed from the bags using a clean pipette for measurement in the

spectrophotometer. Since the same spectrophotometer is used for both the G-value and dose measurements, the actual quantity determined is $[G(Fe^{3+})\cdot L\cdot\rho\cdot\varepsilon]$.

4.2 Co-60 Irradiation

The PE bag containing the Fricke solution, contained by the PMMA irradiation holder, was positioned inside a 30 × 30 × 30 cm^3 water phantom at a water-equivalent reference depth of 5.3 cm, with a source surface distance of 100.0 cm and a field size of 10 × 10 cm^2. The irradiation time was 1200 s, and the source dose rate to water was 1.75 × 10^{-2} Gys^{-1}. As for the Ir-192 irradiations, null controls were required, with the Fricke solution kept inside the bags for the same period of time of 1200 s. The controls were measured twice a day, once before the first irradiation, and once after the last irradiation. The readings were performed in the same manner as the readings of the Ir-192 irradiations.

4.3 X-Ray Irradiation

The procedure for the x-ray measurements was basically the same as for the Co-60 irradiations, except the irradiations were carried out in-air, rather than in-phantom. The same PMMA holder as for Co-60 was used and this was positioned so that the PE bag was at the reference point where the air kerma was known. The generating potential was 250 kVp and the effective photon energy was calculated to be 126 keV (this is the same beam quality and geometry as used by McEwen *et al*, 2014).The mean absorbed dose to the Fricke solution is determined from a primary measurement of air kerma (using the NRC primary standard free air chamber) and a kerma-to-dose conversion factor obtained by NRC, using the EGSnrc Monte Carlo code (Kawrakow, *et al*, 2013).

4.4 G-value for Ir-192

From the two G-values obtained it is relatively straightforward to determine the G-value for Ir-192, although the interpolated value has a small dependence on the choice of mean energy for Ir-192 (0.1 % per 10 keV shift in mean energy). There is also an uncertainty associated with the assumed energy dependence of the G-value in the region of interest (linear or quadratic), which amounts to approximately 0.3 %. The assumption used for the NRC determination is that the G-value and effective photon energy have a log-linear relationship.

5. Absorbed Dose to Water Determination

The quantity absorbed dose to water, D_w, is derived from the absorbed dose to the Fricke solution as follows:

$$D_w = D_F \cdot f \cdot p_{wall} \cdot F_h \cdot k_{ru} \qquad (4)$$

where

D_F is the absorbed dose in the Fricke solution, as given in equation (1);

f is the dose conversion factor due to the difference in radiation absorption characteristics and density of Fricke and water solution;

p_{wall} is the correction factor for the effect of any holder (in this case the PMMA holders shown in Figures 1 and 2);

F_h is the axial dose homogeneity correction due to the volume-averaging effect;

k_{ru} *is* the radial correction factor due to the non-uniformity of the dose profile over the solution volume.

a) **LCR** - all the correction factors were determined by Monte Carlo calculations, using the PENELOPE code (Salvat *et al*, 2009). Although modern Monte Carlo codes allow the user to easily make the conversion directly from D_F to D_w each factor was evaluated

independently to more easily account for changes in the setup, permit sensitivity studies, and allow comparisons between the two group's approaches.

The cut-off energy for electrons was 10 keV and that for photons was 1.0 keV; relevant PENELOPE parameters were set to C1=C2=0.05 and Wcc=Wcr=1.0 keV. The active source used was the Ir-192 bare spectrum published by Borg and Rogers (1999); for each simulation run, 10^9 primary particles (photons) were distributed in 10 processes using the clonEasy application (Badal and Sempau, 2006), thereby providing values of the dose to the sensitive volume with statistical uncertainties below 0.1 %. To simulate the geometry of the iridium source, the information provided by the Carleton University Website for the NucletronmicroSelectron V2 source was used, as shown in Figure 3.

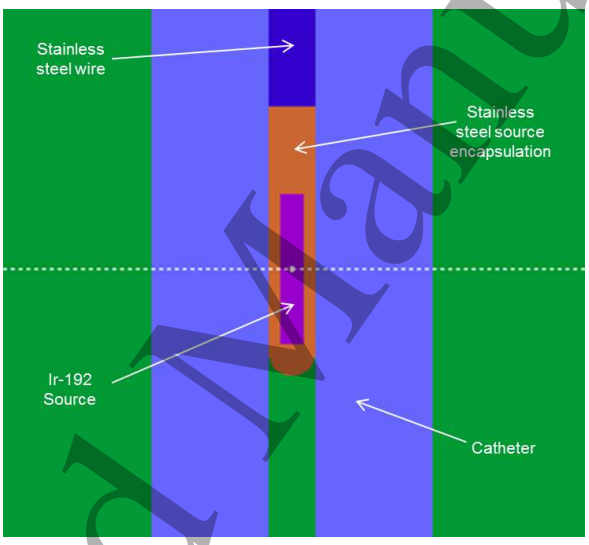

Figure 3. The geometry of the Nucletron microSelectron V2 model used in the simulations. Pink colour represents the Ir-192 core; orange represents the AISI 316L stainless steel capsule (density 8.06 g/cm3); dark blue colour represents the AISI 316L stainless steel cable (density 4.81 g/cm3); and light blue represents the plastic source catheter.

The f factor was obtained as $f = D_w/D_F$ using the same geometry, one with Fricke solution in the detector volume (D_F), and the other one with water in the detector volume (D_w). The geometry used in PENELOPE for this determination is shown in Figure 4.

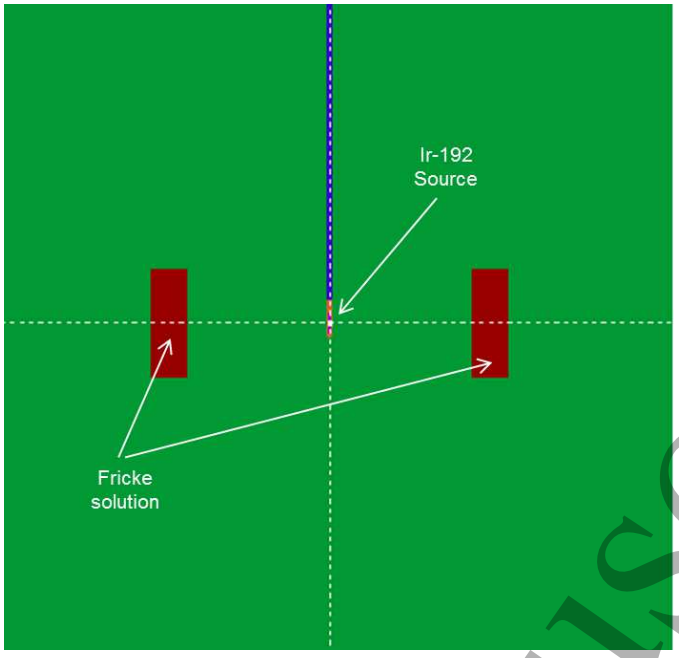

Figure 4. Determination of the f factor - the geometry used for the determination of the ratio between absorbed dose to water and absorbed dose to Fricke solution. The red squares represent the Fricke solution volume (which is actually a ring in 3-D). The source is in the centre of the "crosswires" and the blue line represents the catheter for the source. The green represents the (wall-less) water phantom.

The p_{wall} factor was obtained as $p_{wall} = D_F / D_F'$, where D_F is the absorbed dose to the Fricke solution in a wall-less volume detector, and D_F' is the same quantity obtained in a PMMA wall vessel and with the polyethylene (PE) vessel that served as the water phantom. This geometry used for the calculation is shown in Figure 5.

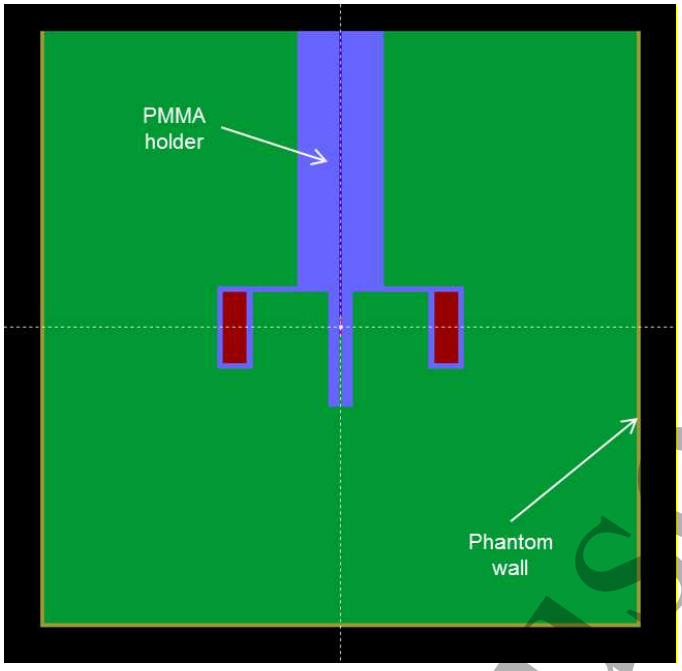

Figure 5. Determination of the p_{wall} factor - the geometry used for the determination of the wall perturbation (PMMA walls and the PE beaker are included in one factor). The added components from Figure 4 are the PMMA of the holder (blue) and the polyethylene water phantom (beige).

The F_h factor was obtained by taking the ratio of the absorbed dose to Fricke solution in a small cylindrical ring (0.12 cm thick and 1.8 cm in height) in the centre of the real volume detector to the absorbed dose to Fricke solution in the whole detector volume (a cylindrical ring with 0.6 cm of thickness and 1.8 cm height), as schematically illustrated in Figure 6. This factor corrects for the radial fall-off of the depth-dose curve.

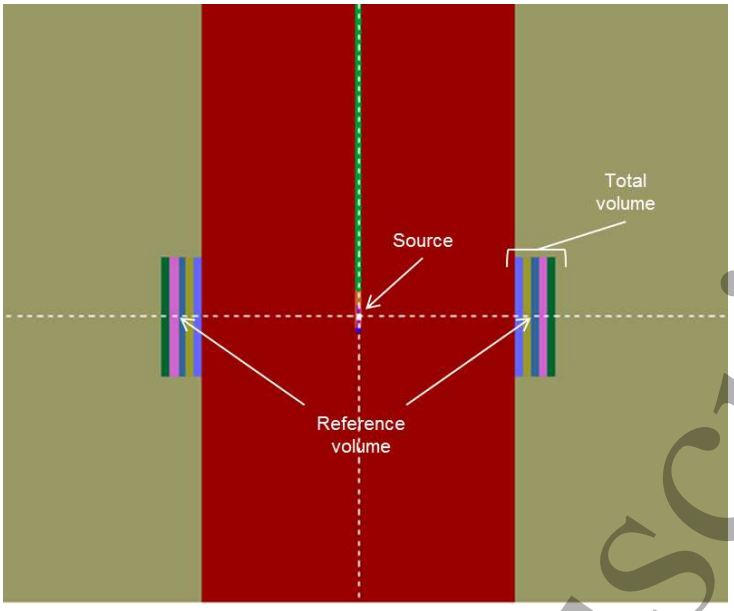

Figure 6. Determination of the the F_h factor. The series of lines subdivide the detector volume, the dark blue cylindrical ring in the centre of the detector volume represents the reference volume used to estimate the volume averaging effect of the actual detector. The source is at the centre of the image and the other colours are simply used for contrast.

The k_{ru} factor was obtained by taking the ratio of the dose to the Fricke solution in a small cylindrical ring (0.6 cm thickness and 0.2 cm height) in the centre of the real volume detector to the absorbed dose to Fricke solution in the whole detector volume (a cylindrical ring with 0.6 cm of thickness and 1.8 cm height), as illustrated in Figure 7.

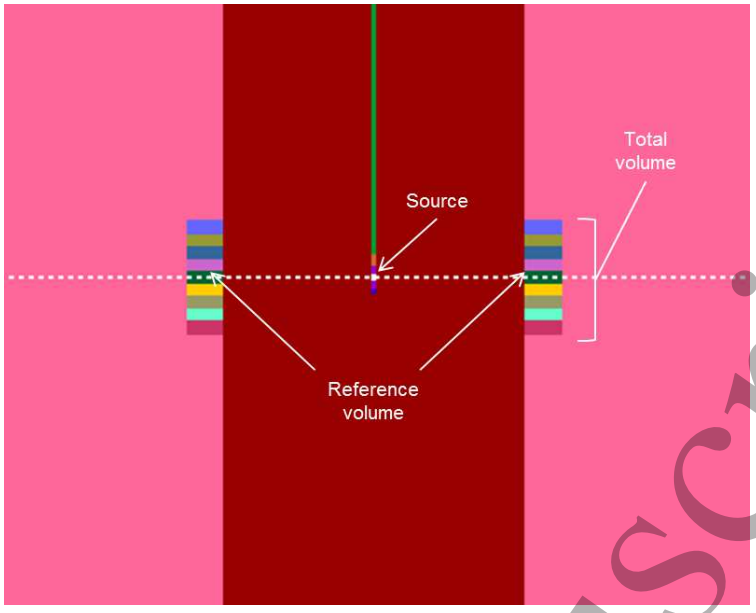

Figure 7. Determination of the k_{ru} factor. As for Figure 6, the detector volume is subdivided into smaller volumes and the dark green cylindrical ring in the centre of the volume detector is the reference used for estimate the axial anisotropy effect. The other colours are used to provide contrast.

b) **NRC** – Equation (3) is also used for the NRC standard, although the F_h and k_{ru} corrections are combined into a single factor k_{dd}. The various factors were evaluated using a similar approach to the one described above, the main differences being that the volume averaging correction is calculated directly as the ratio of the dose to water in an infinitesimal cylindrical ring (0 cm thickness and height) to the dose to water in the whole detector volume, and EGSnrc rather than PENELOPE is used to simulate the NRC irradiation geometry. More details about the approach used can be found in El Gamal *et al* (2015).

c) **LCR/NRC dose ratio** – in addition to the correction factors described above, for the comparison of the NRC and LCR standards (and to apply the Fricke measurements to the TG-43 formalism), a factor is required to convert to the standard reference position of 1 cm in water from the source. The NRC holder was specifically designed to measure at this point but the LCR holder determines the dose at 2.7 cm from the source. As there is a change in the dose rate from 2.7 cm to 1 cm of more than a factor of seven, the correction factor (k_{pos}) was obtained with both PENELOPE and EGSnrc.

After obtaining the dose to water values using the LCR solution, the LCR holder and the LCR cleaning procedure, the dose rate for the Ir-192 source were obtained and compared with the one previously obtained with the NRC standard.

6. Uncertainties

The uncertainties for the LCR and NRC dose determinations, following the ISO GUM (2008), are given in Table 1. The data is specific to a single source characterized in 2014. As shown in El Gamal *et al* (2015), the standard uncertainty in the optical density reading varies somewhat between measurements with different sources. Uncertainties are not separately identified as either Type A or Type B as it was felt this did not provide any additional information useful for the comparison.

Table 1. Uncertainty budgets for the two Fricke systems, determined according to the ISO GUM (2008). Values are given as standard uncertainties and Type A and Type B are not separated in the table.

Component	**LCR**	**NRC**[1]
	u_i **(%)**	u_i **(%)**
ΔOD	0.85	1.39
$G(Fe^{+3})$	1.20	0.62[2]
L	0.05	--------
ρ	0.11	--------
ε	0.35	--------
f	0.20	0.15[3]
p_{wall}	0.20	0.15
F_h	0.21	--------[4]
k_{ru}	0.21	--------
k_{dd}	--------	0.11
k_{pos}	0.21	0.15
Absorbed dose to water	1.58	1.54[5]

[1] Values taken from reference El Gamal *et al*, 2015.

[2] NRC method determines the product $[G(Fe^{3+})\cdot L\cdot\rho\cdot\varepsilon]$.

[3] The NRC and LCR values for the various correction factors include a Type B component.

[4] For the NRC calculations, F_h and k_{ru} are combined in a single factor, k_{dd}.

[5] As seen in El Gamal *et al*, 2015, this uncertainty is higher than subsequent determinations.

7. Results

7.1 $G(Fe^{+3})$ value determinations using NRC methodology

The $G(Fe^{+3})$ values obtained using the NRC methodology but using the LCR Fricke solution, cleaning method and personnel, are given in Table 2, along with difference from the published NRC values. For the LCR interpolations the mean energy of Ir-192 was taken to be 0.380 MeV (the same value was used in the NRC determination).

Table 2. Comparison of the G-value obtained using the NRC methodology

	$G(Fe^{3+})$ ($\mu mol\ J^{-1}$)	**Standard uncertainty**	**Difference from NRC value**
Co-60	1.607E-06	0.5 %	- 0.2 %
X-rays	1.590E-06	1.1 %	+ 1.3 %
Ir-192	1.594E-06	1.2 %	+ 0.3 %

Note, the values in Table 2 should be viewed as strongly correlated with the NRC values in McEwen *et al* (2014), since there are many components in common to the two sets of measurements: same radiation source, same irradiation procedure, same read-out method and same primary standards for Co-60 and kV x-rays.

7.2 Ir-192 absorbed dose to water determinations

For the absorbed dose-to-water comparison, the LCR determination used a value for $G(Fe^{3+})$ obtained from the literature, rather than use the value given above in Table 2. The LCR value was obtained from a curve fitting of the ionometric and calorimetric measurements reported by Fregene (1966) and the calorimetric measurements reported by Klassen *et al* (1999) and this is detailed in de Almeida *et al* (2014). Although it has been noted above that the literature data are not recent, the alternative of using the G-value from Table 2 would result in the two dose determinations being too-closely correlated. The values used for the various parameters in equations (1) and (4) are given in Table 3.

Table 3. Dose to Water determination: LCR methodology

Parameter	**Value**
f	1.0004
p_{wall}	0.9989
ΔOD	0.0472
G(Fe^{3+}) (mol/J)	1.555×10^{-6}
L (cm)	1.0000
ρ (kg/cm^3)	1.0230×10^{-3}
ε (cm^2/mol)	2.174×10^{6}
F_h	0.9969
k_{dd}	1.0391
k_{pos}	7.1932
Doserate (Gy h^{-1})	**369.5**

This value for the absorbed dose rate to water was then compared with the NRC determination and the value provided by the manufacturer (calculated at 1 cm from the source in water) and this is shown in Table 4. All determinations were corrected to the same reference day using the standard value for the half-life of Ir-192 (73.83 days). The uncertainties in the LCR and NRC values are given in Table 1; the standard uncertainty (k=1) for the manufacturer value (based on a National Institute of Standards and Technology, US, primary standard of air kerma) is stated to be 1.7 % on the certificate. This is consistent with that given in AAPM Report TG-138 (2011), (standard uncertainty = 1.5 %).

Table 4. Comparison of the Dose Rate Calculated at 1cm using different standards.

Source	**Dose at 1cm on January 3rd**
Manufacturer value of the dose rate	367.7 Gy/h
LCR calculated dose rate	369.5 Gy/h
NRC calculated dose rate	369.3 Gy/h

8. Discussion

The results for the determination of the G-value for the Co-60 beam quality can be used to directly compare the two methods for preparing the Fricke solution, since all other parameters are common. As can be seen in Table 2, there is very good agreement between the value obtained with the LCR Fricke formulation and the NRC value. It also should be noted that the new NRC value is consistent with the historical data summarized by Klassen *et al* (1999). This finding is consistent with the recommendations in ICRU Report 90, which indicate that the G-value of Fricke is independent of the particular formulation at the ± 0.5 % level.

The data in Table 2 also suggest that the interpolation procedure used by McEwen *et al* (2014) is repeatable within the measurement uncertainties. This is encouraging as the x-ray irradiation procedure is potentially more sensitive to positioning errors, due to the low-mass in-air holder and the potential for the liquid in the PE bag to distort.

Monte Carlo simulations are a fundamental part of many dosimetry standards and that is certainly the case here. Several simulations have been described in detail above or in associated publications and one important aspect of this comparison is that two independent MC codes were used - PENELOPE and EGSnrc. To verify that the comparison results in Table 4 are not skewed by the use of different codes, the two largest corrections factors for the LCR geometry – k_{dd} and k_{pos} – were re-evaluated using EGSnrc. The difference for k_{dd} was of the order of the Type A uncertainties of either calculation (k_{dd} = 1.0379 compared to k_{dd} = 1.0391 for the PENELOPE calculation). For the k_{pos} factor, the agreement between PENELOPE and EGSnrc was also very good, better than 0.2 %. This is perhaps to be expected as the dominant component is the inverse-square correction and the perturbing effect of the PMMA holder will be small.

The results shown in Table 4 are both encouraging and surprising. There is excellent agreement between the dose measurements using the NRC and LCR systems (less than 0.07 %) and both values are with 0.7 % of the manufacturer value, traceable to an air-kerma standard via TG-43. However, the agreement between the LCR and NRC dose rate values is surprising given the different G-values used. Table 2 would suggest that there is no difference in the two Fricke solutions but Table 4 appears to contradict that,

unless the difference in G-values (1.555×10^{-6} vs 1.589×10^{-6} μmol J^{-1}) is being compensated by other correction factors. This last point is unlikely given the good agreement between PENELOPE and EGSnrc, although some error in the simulation geometry used for both calculations cannot be ruled out. In particular, the k_{pos} correction factor is sensitive at the level of 1 % per 0.1 mm shift in measurement position.

It is useful to analyse the impact of the choice of G-value for the LCR results, and this is shown in Table 5.

Table 5. Comparison of the Dose Rate Calculated at 1 cm using different choices of the G-value for Fricke.

G-value used	**Dose at 1cm on January 3rd**	**Difference compared to NRC dose rate value**
Literature value chosen by LCR = 1.555×10^{-6} μmol J^{-1}	369.5 Gy/h	-0.05 %
Value obtained using NRC methodology and LCR Fricke solution = 1.594×10^{-6} μmol J^{-1}	360.5 Gy/h	-2.5 %
Literature value derived by McEwen *et al* = 1.571×10^{-6} μmol J^{-1}	365.7 Gy/h	-1.1 %

As can be seen, the choice of G-value changes the dose ratio compared to the NRC standard by 2.5 %. This spread is consistent with the uncertainty estimate given in Table 1. Although the literature data are quite definitive for higher energy photon and electron beams, there is little experimental data in the energy region of Ir-192 and so further measurements would seem to be needed. Calorimeter-based standards developed for Ir-192 could be suitable for a determination of $G(Fe^{3+})$ without reference to either Co-60 or kV x-rays.

Irrespective of the choice of G-value, it is important to note that the NRC and LCR standards agree within their combined uncertainties and this provides confidence in the technique to determine absorbed dose to water at the reference position recommended by the AAPM TG-43 report without reference to an air kerma measurement.

Finally, it is a positive finding of this comparison that there is no significant dependence on the holder design. The Fricke holders, although based on a similar concept, are very different in their construction and so it is very encouraging to see the excellent level of agreement shown in Tables 4 and 5. Following on from this comment, it is of interest to ask whether this comparison points to an optimal design of holder. The main advantage of the NRC holder is that one measures the dose at 1 cm distant from the source (the TG-43 reference point) but the LCR holder provides significantly more Fricke solution per irradiation and its measuring volume is positioned on a more shallow portion of the depth-dose curve. Monte Carlo simulations are perhaps required to determine the best geometry to optimize these various parameters and this therefore suggests another avenue of further study.

9. Conclusion

Two Fricke-based absorbed dose to water standards for HDR Ir-192 dosimetry, developed independently by the LCR in Brazil and the NRC in Canada have been compared. The agreement in the determination of the dose rate from a HDR Ir-192 source at 1 cm in a water phantom was found to be within the combined measurement uncertainties of the two standards (estimated to be 2.2 % at k=1). The dose-based standards also agreed within the uncertainties with the manufacturer's stated dose value, which is traceable to a national standard of air kerma. A number of possible influence quantities were investigated, including the specific method for producing the ferrous-sulphate Fricke solution, the geometry of the holder, and the Monte Carlo code used to determine correction factors.

This comparison has highlighted the applicability of Fricke dosimetry to Ir-192 measurements.

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