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The Fricke dosimeter as an absorbed dose to water primary standard for Ir-192 brachytherapy

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Abstract

The aim of this project was to develop an absorbed dose to water primary standard for Ir-192 brachytherapy based on the Fricke dosimeter. To achieve this within the framework of the existing TG-43 protocol, a determination of the absorbed dose to water at the reference position, $D_w(r_0,\theta_0)$, was undertaken. Prior to this investigation, the radiation chemical yield of the ferric ions (G-value) at the Ir-192 equivalent photon energy was established by interpolating between G-values obtained for Co-60 and 250 kV x-rays.

An irradiation geometry was developed with a cylindrical holder to contain the Fricke solution and allow irradiations in a water phantom to be conducted using a standard Nucletron micorSelectron HDR V2 Ir-192 afterloader. Once the geometry and holder were optimized the dose obtained with the Fricke system was compared to the standard method used in North America, based on air kerma strength.

Initial investigations focussed on reproducible positioning of the Fricke solution in-holder with respect to the Ir-192 source and obtaining an acceptable type A uncertainty in the optical density measurements required to yield the absorbed dose. Source positioning was found to be reproducible at better than 0.3 mm and a careful cleaning and control procedure reduced the variation in OD reading due to contamination of the Fricke solution by the PMMA holder. It was found that fewer than 10 irradiations were required to yield a type A standard uncertainty of less than 0.5 %.

Correction factors to take account of the non-water components of the geometry and the volume averaging effect of the Fricke solution volume were obtained from Monte Carlo calculations. A sensitivity analysis showed that the dependence on the input data used (e.g., interaction cross-sections) was small with a type B uncertainty for these corrections estimated to be 0.2 %.

The combined standard uncertainty in the determination of absorbed dose to water at the reference position for TG-43 (1 cm from the source, perpendicular from the center of the source, in a water phantom) was estimated to be 0.8 % with the dominant uncertainty coming from the determination of the G-value. A comparison with absorbed dose to water obtained using the product of air kerma strength and the dose rate constant gave agreement within 1.5 % for three different Ir-192 sources, which is within the combined standard uncertainties of the two methods.

1. INTRODUCTION

Fricke dosimetry is a chemical dosimetry system developed by Hugo Fricke (Fricke and Hart, 1966) and, being closely water equivalent and having a high sensitivity in the dose range of interest in radiotherapy, has become the most widely used chemical dosimeter. The main constituents of the dilute aqueous Fricke solution are sulphuric acid and ferrous ammonium sulfate. The dosimeter relies on measuring the ferric ions (Fe^{3+}) produced through the oxidation of ferrous ions (Fe^{2+}) in the solution by water radiolysis products (i.e., it is the interaction of radiation with water that drives the process). The change in ferric ion concentration results in a measurable change in optical density which can be measured by a spectrophotometer. The yield of ferric ions can consequently be related to the dose imparted to the Fricke solution. Fricke dosimetry has seen several applications including its use as a mail order dosimeter (Olzanski *et al*, 2002) and its use by the Swiss national standards laboratory, METAS, as its primary absorbed dose standard for 5.4-22 MeV electron beams (Stucki and Vörös, 2007). For a recent, detailed description of the Fricke dosimeter system the reader is referred to McEwen and Ross (2009).

To date, the American Association of Physicists in Medicine, AAPM, Task Group 43 report (1995) along with its update (2004) forms the basis of brachytherapy dosimetry in North America. The protocol is air-kerma based, i.e., the starting point for the dose determination is the interaction of radiation in an air cavity free in-air and measurements are not made in the final quantity of interest (absorbed dose to water). The ultimate traceability is to a primary standard ion chamber in an Ir-192 beam (e.g., Douysset *et al*, 2008) or via an ion chamber calibration interpolated from other radiation beams (e.g., Rasmussen *et al*, 2011). Although ion chambers themselves can be very accurate in terms of the quantity they measure, the factors required to convert from an in-air measurement to the required absorbed dose in water phantom results in a relatively large uncertainty compared to other high-energy beam deliveries (e.g., Co-60).

The aim of this project was to develop a system to determine the absorbed dose to water, D_w, at the reference position (i.e., 1 cm away from the source on the transverse axis) but independent of any air kerma measurements. This approach means that the TG-43 formalism would be maintained but with a reduced uncertainty on D_w and a more direct link between final quantity and primary standard. This change to a dose-based standard would also mean that one no longer has to rely on a Monte Carlo determination of the dose rate constant, which has been shown to be sensitive to voxel size effects, interaction cross sections and source design (Taylor and Rogers, 2008). Compared to other absorbed dose systems, (e.g., calorimeters) a Fricke dosimeter has the potential to overcome two of the major obstacles associated with measurements close to HDR sources (< 2 cm): it shows no measurable effect of source self-heating, and the cavity (holder) can be modified to reduce the effects of steep source gradients. Sarfhenia and Seuntjens (2010a) showed very clearly the challenges of using a calorimeter for HDR dosimetry. Only through significant signal averaging and the application of 3-D thermal modelling was it possible to differentiate the 'real' radiation induced temperature rise from the heat conducted from the source. This is because calorimeters, for radiation therapy applications, are measuring radiation-induced temperature rises of, typically, 1-10 mK and therefore the source self-heating, although not significant in terms of treatment delivery, is a serious perturbation. By comparison, the Fricke system is only sensitive to temperature at the 1000 mK level, as discussed in section II.

Sarfhenia *et al* (2010b) indicated, through a comparison of various techniques (calorimetry, cavity theory, radiochromic film), that the present TG-43 method is not significantly in error and therefore it was decided to only carry out a direct comparison of the Fricke technique with standards based on air kerma strength. Where such a comparison is made here, a value of the dose rate constant for Ir-192 of 1.109 cGy h^{-1} U^{-1} (CLRP, 2008) was used.

2. METHODS

2.1. A. Basis of Fricke dosimetry

Although the basis of the Fricke dosimetry system is well-established it is worth presenting here as it aids the discussion later. The absorbed dose to the Fricke solution and, subsequently, the absorbed dose to water are respectively given by:

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

$$D_w = D_f \cdot f_{w,f} \cdot P_{wall} \cdot k_{dd} \quad (2)$$

Taking Equation (1) first, the net change in optical density, measured using a spectrophotometer, is denoted by ΔOD_{net} . In order to determine the absorbed dose to the Fricke solution, this quantity has to be divided by the product of ρ, the Fricke solution density, taken to be 1.0227 x 10^{-3} kg cm^{-3} at 25 °C (Olszanski *et al*, 2002), and *d*, the optical path-length of the cuvette used for readout. The optical path length of a cuvette is defined as the product of the distance traversed by light through the cuvette and the refractive index of the cuvette. For this work (1 ± 0.0002) cm (Klassen *et al*, 1999) optical path length cuvettes were used.

The molar linear absorption coefficient, denoted by ε, quantifies the effect of one mole of ferric ions on the optical density reading, and is analogous to an attenuation coefficient in the transmission of x-rays through a medium. The molar linear absorption coefficient is a constant chemical property of the ferric ions and has been measured at 25 °C to be 2174 x 10^3 cm^2 mol^{-1} (Cottens *et al*, 1981). The radiation chemical yield of the ferric ions, (Fe^{3+}) , or G-value completes Equation (1) and represents the number of moles of ferric ions produced per joule of energy deposited in the Fricke solution. To account for the temperature dependence of the procedure the following relationship is used to convert the optical density readings at an arbitrary irradiation temperature and readout temperature to one at the reference temperature of 25 °C (Shortt, 1989; Klassen *et al*, 1999):

$$\Delta OD_{net\ 25,25} = \Delta OD_{T_{irrad},T_{read}} \cdot [1 + 0.0012(25 - T_{irrad})][1 + 0.0069(25 - T_{read})] \qquad (3)$$

The intrinsic value and energy dependence of the ferric ion yield arises from details of the radiation chemistry of the solution. Although models can predict the general trend, they are not yet sufficiently developed to be used for precision dosimetry, so measured data must be used. Equation (1) shows the inherent limitation of the Fricke dosimeter, in that the determination of $G(Fe^{3+})$ requires a separate method of determining D_F. This would appear to be an insurmountable problem if one is aiming to use Fricke solution in a radiation beam where such standards are not currently available. The approach taken to avoid this circular argument is described in detail by McEwen *et al* (2014). In essence, it follows the same approach as originally proposed by Goetsch *et al* (1991) for the determination of air kerma in an Ir-192 radiation field, where a calibration coefficient for an ion chamber is derived from standards at other energies.

The conversion from dose to Fricke to dose to water, as shown in Equation (2) typically includes the effect of the holder material, P_{wall}, the dose non-uniformity over the Fricke solution volume, k_{dd}, and the difference in radiation absorption properties of the Fricke solution and water, $f_{w,f}$. Traditionally, Fricke solution has been irradiated in glass vials or quartz holders and therefore the biggest challenge has been in the determination of P_{wall} (Ma *et al*, 1993). The correction for dose non-uniformity comes about as a trade-off between the desire to determine dose at a point and the need for sufficient volume of solution to measure the change in optical absorbance. The correction from Fricke solution to water is generally straightforward, given that the Fricke solution is more than 90 % water.

2.2. Fricke Holder

Figure 1 shows the PMMA holder constructed at the NRC and used for irradiating the Fricke solution, and a schematic of the holder is shown in Figure 2. The starting point for the design of the holder was the work of Austerlitz *et al* (2008) and there are clearly similarities to that design.

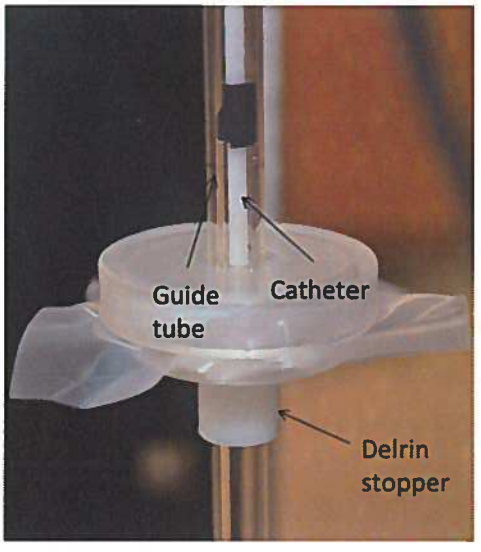
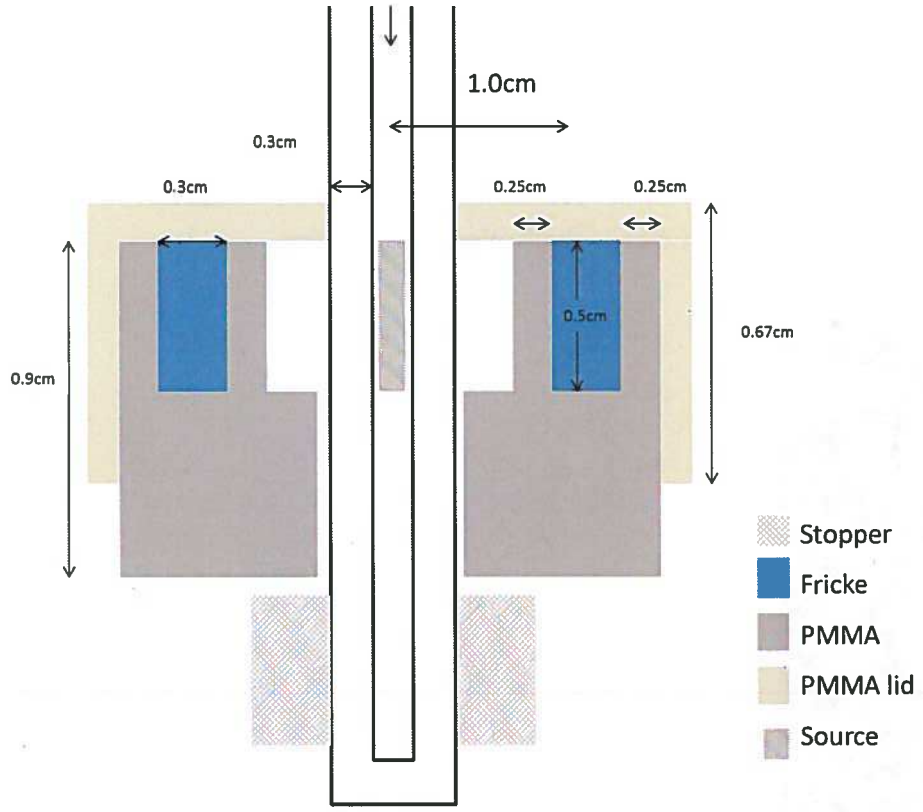


Figure 1: Mounted Fricke holder, the holder is then submerged in a 15 cm x 15 cm cylindrical phantom for irradiations. The holder is manufactured entirely from PMMA except for the method of sealing the Fricke solution in the ring cavity, which uses a combination of thin PTFE and Parafilm M™ films sandwiched between the upper and lower PMMA pieces. The Delrin™ stopper is used to position the holder at the correct position relative to the Ir-192 source.



(b)

Figure 2: Fricke holder cross-section, blue regions represent Fricke solution. The iridium source is shown as the shaded rectangle in the middle of the guide tube. For clarity the Parafilm M ™ and Teflon seals are omitted from the diagram in addition to the catheter within the guide tube (all can be seen in Figure 1). Also, the thin, clinical catheter is not shown in this schematic, although it is clearly seen in Figure 1. All unshaded components may be modeled as water. Note – there is water between the guide tube and the catheter but that there is an air gap above and below the source inside the catheter.

A ring shape was chosen to maximize the volume of Fricke solution around the source while minimizing the dose fall-off over the solution volume with transverse distance from the source. PMMA was used primarily for its ease of machining and close water equivalence compared to glass vials conventionally used for Fricke irradiations. The holder is submerged in a 15 cm x 15 cm cylindrical phantom for irradiations.

Impurities, organic ones in particular, can cause changes in the optical density of the Fricke solution resulting in lower precision. One of the potential issues with non-glass holders is the difficulty in cleaning and the potential for leaching of impurities from the walls. The use of PMMA holders with doses <10 Gy was achieved by developing a stringent cleaning protocol based on the work of Olzanski *et al* (2002) and described in detail by El Gamal (2013). In addition to the cleaning, there must be no chance of contamination from the water used in the phantom for irradiation. A seal consisting of a Teflon disk held in place by a piece of Parafilm M™ plastic film was found to provide the necessary isolation of the Fricke solution. In Figure 1 one can clearly see the piece of Parafilm between the two PMMA pieces of the holder.

2.3. Source positioning

As can be seen from Figure 2, knowledge of the source position is necessary in order to align the center of the Fricke holder cavity with the center of the source. An IBA EFD diode was **mounted** on a linear translator that allowed the operator to scan the length of the catheter (vertically in Figure 1, with the Fricke holder removed). By assuming the position of maximum diode signal occurred when the centre of the diode was aligned with the centre of the seed, the position as recorded by the scanning system could then be transferred to a telescope, which was then used to define the reference position for mounting the Fricke holder correctly in relation to the source position. A typical result is shown in Figure 3 and repeated measurements showed that the diode was able to determine the position of the seed with a resolution of ± 0.1 mm. Measurements were made with a number of different detectors (diodes, micro ionization chambers) to confirm that the measurement point of the EFD diode was at the geometric centre of the front face of the detector.

For convenience the diode measurements were conducted in air. The determination of the seed position was done once at the beginning of each irradiation day, even if the source position was not changed from the previous day. The treatment planning system was observed to consistently reproduce the seed position to within 0.3 mm, although larger variations were observed when switching back and forth between different treatment plans and/or after a source change. This indicates the importance of having an HDR afterloader system exclusively for the development and provision of absorbed dose standards.

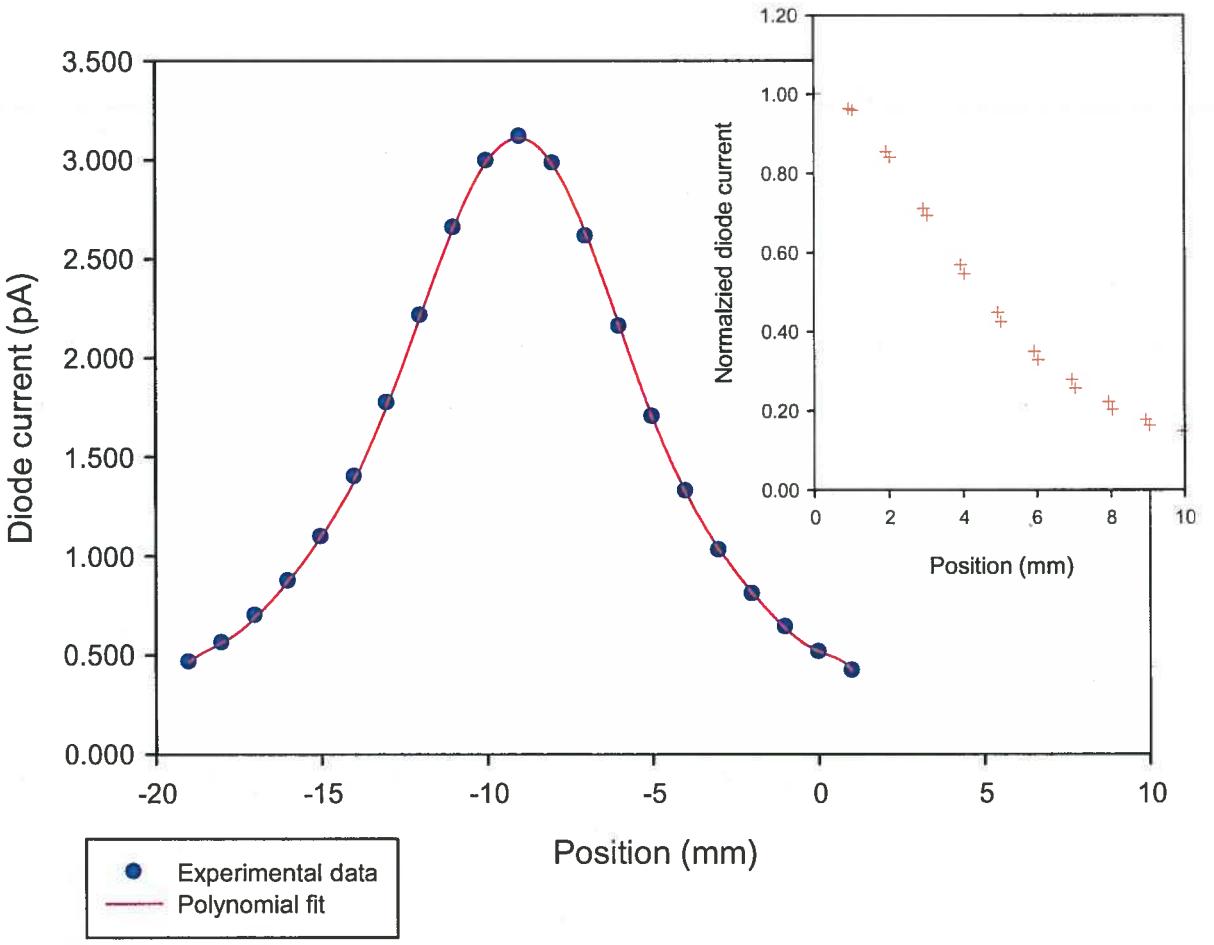


Figure 3: A plot of the diode signal versus relative diode position, 0 mm denotes the arbitrary reference position for the scanning system. A high-order polynomial fit is used to determine the position of the peak of the curve, which is assumed to show the position of the seed center. The inset shows mirrored

data, with little asymmetry, indicating that the radioactivity within the source is homogeneous and that the diode is scanned parallel to the source axis.

2.4. Readout

A modified Cary 400 spectrophotometer (Olszanski *et al*, 2002) is used to measure the optical density. The sample compartment containing the cuvettes is maintained at 25.00 ± 0.01 °C and compressed nitrogen (100 $cm^3\ s^{-1}$) is used for purging, to limit contamination of the spectrophotometer's optics. A custom program allows the readout process to be automated. During readout the sample compartment can hold two cuvettes, an empty sample compartment and a standard absorbance filter. A 30 % transmittance metal-on-quartz standard absorbance filter (NIST SRM-2031) is used with an expected absorbance reading at 303 nm of 0.355 optical density units. The role of the filter is to verify the reliability of the absorbance readings, given the potential effects of baseline drift or misalignment of the sample compartment with the optical components of the spectrophotometer.

2.5. Monte Carlo calculations

Obtaining the dose to water of an ^{192}Ir HDR microSelectron V2 seed from in-phantom Fricke measurements requires a set of three corrections factors to convert the dose to the Fricke solution to dose to water at a point 1 cm away on the transverse axis of the ^{192}Ir seed (Equation (2)). The experimental setup (see Figures 1 & 2) was faithfully modelled including the microSelectron V2 ^{192}Ir HDR seed, the polypropylene water phantom (not shown), the PMMA holder and the PMMA catheter using the EGSnrc user-code **cavity** (Kawrakow *et al*, 2013). Making use of the possibility of simulating several geometries at the same time, a correlated scoring of doses allows an efficient estimation of the factors $f_{f,w}$ and P_{wall}. A 0.01 % one-sigma statistical uncertainty is achieved after 3 billion histories.

The volume averaging correction, k_{dd}, requires additional calculations with the user-code **cavity**. We chose to start by varying the radial thickness of the cylindrically symmetric sensitive volume from 0.025 cm up to 0.32 cm, while fixing the sensitive volume's height at its actual value of 0.517 cm. Note that the actual radial thickness of the sensitive volume defined by the PMMA holder is 0.298 cm. The dose to the sensitive volume as a function of the radial thickness is then fitted to an analytical expression from which a zero-thickness value can be extrapolated. The one-sigma statistical uncertainty in the radial correction is less than 0.01 % after 6 billion MC histories. The same procedure is repeated for the sensitive volume's height using a radial thickness of 0.025 cm since the dose varies by less than 0.01% from the dose for zero radial thickness. The one sigma statistical uncertainty in the height correction is 0.04 % after 570 million MC histories, and consequently, the overall one sigma uncertainty in the k_{dd} correction is estimated to be 0.04 %.

3. RESULTS

3.1. G-value Determination

McEwen *et al* (2014) give a value for $G(Fe^{3+})$ for the mean energy of Ir-192 as 1.589 ± 0.009 μmol J^{-1}. Alternatively the quantity $[\varepsilon \cdot G(Fe^{3+}) \cdot \rho \cdot d]$, which is actually what is required for Equation (1) in this case since all measurements use the same Fricke solution and readout, has a value of 0.003533 ± 2.2 x 10^{-5} Gy^{-1}. This is the most accurate value for G at this energy obtained to date and agrees with the historical data compiled by Klassen *et al* (1999) within estimated measurement uncertainties.

3.2. Precision of Fricke measurements for determination of D_w

Table 1 shows the standard uncertainty of the optical density readings for two independent experiments involving the same microSelectron V2 Ir-192 seed. The irradiator was set to give the source a dwell time of 10 minutes (600.0 s) for each irradiation. It should be noted that each result in a given experiment is corrected for source decay relative to the first reading taken in that data set. The lower net optical density readings for January 2013 compared to December 2012 are therefore a result of source decay. The standard deviation of the optical density measurements combines a number of components, including reproducibility of the positioning method, control of contamination, and the dose delivery system. The increased relative standard deviation for the second set of measurements is consistent with the reduced readout signal due to source decay. Although the irradiation time is relatively short, the complete readout procedure is lengthy and typically no more than 3 irradiations can be completed each day.

Table 1. Results of Fricke optical density readings for two different microselectron V2 Ir-192 seeds.

Date	December 2012	January 2013
Number of runs	6	6
Net optical density	0.2273	0.1581
Standard deviation	0.8 %	1.2 %
Standard uncertainty	0.3 %	0.5 %

3.3. Correction factors

Table 2 shows the values of the correction factors determined using the EGSnrc Monte Carlo system, together with a fourth correction factor, k_{pos}, which is discussed in Section IV.

Table 2. Values for correction factors required in Equation (2) to convert from absorbed dose to Fricke to absorbed dose to water.

	Value	Type A Standard uncertainty	Type B Standard uncertainty
$f_{w,f}$	1.0019	0.01 %	0.15 %
P_{wall}	0.9988	0.01 %	0.15 %
k_{dd}	1.0151	0.04 %	0.10 %
k_{pos}	0.9996	---	0.15 %

3.4. Determination of absorbed dose to water at the reference point

Table 3 shows the values and uncertainty budget for the NRC absorbed dose to water determination, based on the source decay-corrected $D_w(r_0,\theta_0)$ for three further investigations in 2013 and 2014 using three different Ir-192 sources. In this case, the irradiation time was adjusted, where necessary, to take account of source decay and yield similar values of the net optical density.

Table 3. Summary of results and uncertainty budget for the determination of $D_w(r_0,\theta_0)$ using the NRC Fricke Dosimetry system. NOTE - to simplify the table the depth-dose correction, which is holder-specific, has been applied to the corrected OD reading.

	Value	Type A Standard uncertainty	Type B Standard uncertainty
ΔOD_{corr} (source #1)	0.25813	1.36 %	0.28 %
ΔOD_{corr} (source #2)	0.21415	0.63 %	0.28 %
ΔOD_{corr} (source #3)	0.21712	0.33 %	0.28 %
$[\varepsilon \cdot G(Fe^{3+}) \cdot \rho \cdot d]$ (Gy^{-1})	0.003533	---	0.62 %
Correction factors (MC only)	1.0158	0.05 %	0.20 %
POM correction, k_{pos}	0.9996		0.15 %
$D_w(r_0,\theta_0)$ (Gy h^{-1}) (#1)	**74.19**	**1.54 %**	
$D_w(r_0,\theta_0)$ (Gy h^{-1}) (#2)	**369.31**	**0.97 %**	
$D_w(r_0,\theta_0)$ (Gy h^{-1}) (#3)	**377.59**	**0.80 %**	

Table 4 shows the dose to water value at the reference position obtained for all experiments compared with i) an air-kerma (TG-43) based determination at NRC, and ii) the manufacturer's stated value. An uncertainty of 1.5 % was estimated for the manufacturer determination based on the TG-138 report (DeWerd, 2011). The uncertainties in the air-kerma calibration method used at NRC are currently being re-evaluated and are likely to be less than this value. These other two methods provide only a determination of the air-kerma strength, which was then multiplied by the dose rate constant, 1.109 $cGyh^{-1}U^{-1}$ (CLRP, 2008), to obtain $D_w(r_0,\theta_0)$.

Table 4. $D_w(r_0,\theta_0)$ results, given as the dose delivered in 1 hour, for three investigations compared with air-kerma based determinations by both the NRC and the manufacturer.

Date	$D_w(r_0,\theta_0)$ (Gy) Fricke	$D_w(r_0,\theta_0)$ (Gy) Air kerma	diff (F_{NRC}-AK_{NRC})	$D_w(r_0,\theta_0)$ (Gy) Manufacturer	diff (AK_M-AK_{NRC})
Jun-13	74.2	75.5	**-1.8 %**	75.3	-0.3 %
Jan-14	369.3	367.4	**0.5 %**	367.7	0.1 %
Sep-14	377.6	383.9	**-1.6 %**	382.2	-0.4 %

4. DISCUSSION

4.1. Effect of irradiation geometry

As noted above, the positioning method used in this work gives the user the ability to locate the seed within the catheter prior to each irradiation and align the holder independently of the treatment planning system, eliminating what has previously been a significant contribution to the overall uncertainty (Austerlitz *et al*, 2008). Optical methods were investigated with the aim of locating the seed *in situ* for each irradiation with the Fricke holder in place. However, the opacity of the catheter led to a uncertainty in position location greater than the 0.3 mm value obtained from the measurements with the diode described earlier. One possibility would be to add a piece of radiochromic film, either between the holder and catheter, or around the outside of the holder. This would potentially allow a retrospective correction for any source/holder misalignment. However, the data in Tables 1 and 3 suggest that the positioning method used does not introduce any significant run-to-run variation.

Two effects that could affect the dose measured by the Fricke solution became apparent during the initial investigation summarized in Table 1. Both are related to the failure of components – specifically the inner cather and the PMMA holder itself – and the steepness of the depth-dose curve

around a Ir-192 HDR seed. Due to radiation damage, the catheters typically failed after 10-20 irradiations and there was concern that manufacturing variations in these components would lead to a shift of the effective point of measurement of the Fricke solution. Thickness measurements on a number of catheters indicated that this concern was groundless. For the holder, failure was due to stress placed on the PMMA outer shell in ensuring a good seal of the Fricke solution from the surrounding water (see Figure 1). PMMA is prone to cracking after machining and even with post-manufacture annealing it was found that holders typically failed more often than the catheters. This is not particularly an issue since the components are easy to reproduce but it was found that slight errors in machining led to one set of holders having a significantly different point of measurement than others. The difference was small, but with a depth-dose gradient at the point of measurement of 200 % cm^{-1} this led to an error of 4% in the dose measured. An additional multiplicative correction, k_{pos}, was therefore added to Equation (2) to take account of this potential variation (and shown in Table 2 for the one of investigations summarized in Table 3). Manufacturing tolerances were tightened up as well - all the holders used for the measurements described in Table 3 positioned the measurement point at (1.000 ± 0.004) cm. The third data set in Table 3 provides a validation of this depth-dose correction in that two holders were used with slightly different dimensions – one placed the measurement point at 0.9965 cm and the other at 1.0040 cm. Based on the depth-dose gradient this should give a difference of 1.5 % in the dose measured with the two holders and the measurement yielded a difference of 1.35 %. An initial investigation is underway to look at the effect of using POM (Delrin™) for the holder material as it is much less prone to cracking. Contamination of the Fricke signal appears to be manageable through the use of controls but the opacity of POM makes its use less desirable than PMMA.

As noted earlier, the irradiations were performed, for convenience, in a cylindrical water phantom of diameter 15 cm and depth 15 cm. This does not correspond to the definition in TG-43 where a 30 cm phantom is specified and therefore Monte Carlo simulations were carried out to investigate the

magnitude of any effect of phantom size. It was found that any significant correction (defined as being greater than 0.1 %) only occurred if the irradiation was not carried out in the centre of the phantom and was less than 5 cm from the water surface.

4.2. Precision of method

The basis of this Fricke-based absorbed dose standard is the ability to obtain precise optical density measurements (standard uncertainty < 0.5 %) using plastic holders at dose levels less than 20 Gy. The results in Table 1 indicate that three major issues have been addressed: developing a method to accurately and repeatably position the holder relative to the Ir-192 source; the use of controls to correct for any contamination of the readout signal due to the plastic holder; and a comprehensive cleaning procedure to ensure no cross-contamination during readout (e.g. between control and irradiated samples). Given the data in Table 1, one can conclude that the method used here exceeds that of the ASTM standard E1026 (ASTM, 2013), where doses are limited to greater than 20 Gy. Monitoring of the effects of contamination (through the correct use of control readings) is essential but the results presented here indicate that the Fricke solution can be left in plastic containers for periods of up to several hours without a significant impact on the overall uncertainty. This has implications for extensions of the method and potentially allows irradiations off-site from where the Fricke solution readout occurs.

An important finding from Table 1 is that the desired standard uncertainty can be achieved with only a small number of irradiations. At the beginning of this project it was thought that, given the relative complexity of the irradiation and readout procedure, tens of irradiations would be required to obtain a standard uncertainty below 0.5%. This would make it unfeasible to characterize every Ir-192 source used (assuming a source change at least every 90 days). In that situation, the application of the

Fricke system would be better suited as a method to obtain an experiment value of the dose rate constant and continue with dissemination via air kerma. However, Table 1 indicates that six runs may be sufficient, which makes it realistic to characterize every source installed in the afterloader. Recent experience with source changes in 2014 has confirmed this view.

4.3. Correction factors

The intention, in designing the Fricke holder (Figure 2) was to only use materials with densities and radiation properties close to that of water. This should mean that any correction factors calculated using Monte Carlo methods are relatively insensitive to input parameters (e.g., stopping powers, cross-sections, *etc*). Also, the fact that all corrections are ratios of dose calculations (comparing the actual geometry with a homogeneous volume of water) will minimize any dependence on basic data. As can be seen in Table 2, this was indeed the case, with Type B uncertainties stemming from interaction coefficients and uncertainties in the modelled geometry being less than 0.2 %.

When using a particular Monte Carlo code to determine important correction factors, the question arises as to its accuracy. One can ensure that the geometry is specified correctly and one can investigate influence quantities such as input data or uncertainties in material composition but one still relies on the underlying accuracy of the radiation transport algorithms used. An opportunity arose during this investigation to compare the EGSnrc results with independent calculations using the PENELOPE code (Salvat *et al*, 2008). A comparison was carried out with another research group developing a similar Fricke-based method (Salata *et al*, 2014) and, as part of this comparison, the ability of EGSnrc and PENELOPE to determine the required correction factors was investigated. Excellent agreement was found between the two codes, with differences less than 0.1 %.

4.4. Accuracy and validation of the method

As shown in Table 3, the achievable relative standard uncertainty of the Fricke based $D_w(r_0,\theta_0)$ determination was estimated to be 0.80 %, which is lower than the target of 1 % set at the beginning of this project. The uncertainty obtained for the first irradiation shown in Table 3 is significantly greater than this and is due to the much lower dose rate (74 Gy hr^{-1} vs 370 Gy hr^{-1}). These low doserate measurements were made with a 'cold' source, more than 2 half-lifes after source installation, and irradiation times had to be extended to 3600 s to obtain a measurable value of the optical density. Increased irradiation time meant that fewer irradiations could be performed and the Fricke solution was in the PMMA holder for longer, and this resulted in the high value for the type A standard uncertainty. Based on this difference in the irradiation procedure, the type B uncertainty should perhaps also be increased but for consistency across all irradiations the same value for that component has been used in Table 3. The main reason for including this data set is to show that the Fricke system is not limited to measurements using a 'hot' source immediately after installation.

The combined uncertainty of 0.8 % is lower than for current air-kerma based determinations and compares very well with calorimeter-based standards. In addition to the work of Sarfhenia and Seuntjens (2010a), several National Metrology Institutes, including NPL (UK), PTB (Germany), ENEA (Italy) and VSL (Netherlands), are in the process of developing absorbed dose to water standards for Ir-192 brachytherapy, based on both graphite and water calorimeters (Selbach *et al*, 2012). Currently published data indicated that a calorimeter-based determination can yield $D_w(r_0,\theta_0)$ with an estimated standard uncertainty of 1.4 - 1.8 % (Sarfhenia *et al*, 2010b, Selbach *et al*, 2012). One of the main draw

backs of calorimeters is the need to take measurements at $r \geq 2$ cm, to avoid the large temperature gradients caused by source self-heating. As noted earlier, this is something to which the Fricke system is insensitive, although measurements at a larger distance are potentially attractive as this would either (i) increase the volume of Fricke irradiated (and allow multiple OD measurements from a single measurement) or (ii) allow the height of the Fricke volume to be reduced to approximate more closely the 1-D definition in TG-43 and reduce the uniformity correction in Table 2.

The two air kerma-based methods given in Table 4 are traceable to different national standards and therefore the agreement between them gives some level of validation of the NRC standard that is currently used to disseminate HDR Ir-192 dosimetry in Canada (Mainegra-Hing and Downton, 2014). There is also an international comparison program currently underway (BIPM, 2014), organized by the Bureau International des Poids et Mesures (BIPM), and NRC has recently participated. The initial results from this indicate that the NRC air kerma method is consistent with other national laboratories at the level of the measurement uncertainties. It is therefore reasonable to take the NRC air kerma value in Table 4 as being valid to use in comparing with the Fricke-based value.

An alternative perspective on the data in Table 4 is that it provides an experimental determination of the dose rate constant, currently the result of a Monte-Carlo calculation. An analysis of the difference between the NRC dose and kerma methods reported in Table 4 would indicate that the dose rate constant should be reduced by 1.0 % (based on a weighted mean analysisyielding a value of $\Lambda = 1.098$ cGy h^{-1} U^{-1} This change is in the opposite direction from the MC value to that reported by Selbach *et al* for a calorimeter-based determination of Λ (1.113 cGy h^{-1} U^{-1}). However, as seen from Table 4, the agreement between the two methods is within the 95% confidence limit of either method *alone*, and therefore there is no indication of any error in HDR dosimetry disseminated via the air kerma method, and no reason to consider an experimentally-derived value of Λ until more data is available

from a number of sources. Sarfhenia *et al* (2010b) reached the same conclusion as to the reliability within measurement uncertainties of the present air-kerma method and the fact that there are now multiple methods giving similar results provides a high level of confidence in the dissemination of absorbed dose to water for HDR Ir-192 brachytherapy dosimetry.

Alanine is another chemical dosimeter that has been applied to the dosimetry of brachytherapy. Although generally limited to Co-60 energies and above, the recent work of Anton *et al* (2015) would suggest that the challenges of volume averaging and energy response of that detector are being addressed. However, alanine is a secondary dosimeter and therefore more comparable with radiochromic film, but the techniques developed for alanine may provide useful insight into the measurement issues for Frick-based systems such as used here.

The success of the approach taken here suggests that it could lead to further applications for the Fricke dosimetry system. Possibilities include determining the mean dose to an arbitrary volume for comparison with 3D treatment plans. This moves away from the traditional approach of measurement at a point but perhaps more closely reflects the endpoint of treatment delivery where the whole tumour volume is the target.

5. CONCLUSION

An absorbed dose to water primary standard for Ir-192 brachytherapy based on the Fricke dosimeter has been developed that fits within the framework of the existing TG-43 protocol, yielding a value of the absorbed dose to water at the reference position, $D_w(r_0,\theta_0)$. The radiation chemical yield of the ferric ions (G-value) at the Ir-192 equivalent photon energy, necessary for the

application of the Fricke dosimeter, was established by interpolating between G-values obtained for Co-60 and 250 kV X-rays in an earlier investigation.

An irradiation geometry was developed with a cylindrical holder to contain the Fricke solution and allow irradiations in a water phantom to be conducted using a standard Ir-192 afterloader. Once the geometry and holder were optimized the dose obtained with the Fricke system was compared to the standard method used in North America, based on air kerma strength.

Initial investigations focussed on reproducible positioning of the Fricke solution in-holder with respect to the Ir-192 source and obtaining an acceptable type A uncertainty in the optical density measurements required to yield the absorbed dose. Source positioning was found to be reproducible at better than 0.3 mm and through a careful cleaning and control procedure it was found that fewer than 10 irradiations were required to yield a type A standard uncertainty of less than 0.5 %.

Correction factors to take account of the non-water components of the geometry and the volume averaging effect of the Fricke solution volume were obtained from Monte Carlo calculations. A sensitivity analysis showed that the dependence on the input data used (e.g., interaction cross-sections) was small with a type B uncertainty for these corrections estimated to be 0.2 %.

The combined standard uncertainty in the determination of absorbed dose to water at the reference position for TG-43 (1 cm from the source, perpendicular from the center of the source, in a water phantom) was estimated to be 0.8 % with the dominant uncertainty coming from the determination of the G-value. A comparison with absorbed dose to water obtained using the product of air kerma strength and the dose rate constant gave agreement within 1.5 % for three different Ir-192 sources, which is within the combined standard uncertainties of the two methods.

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