A practical implementation of the 2010 IPEM high dose rate brachytherapy code of practice for the calibration of $^{192}$Ir sources

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Corrigendum

A practical implementation of the 2010 IPEM high dose rate brachytherapy code of practice for the calibration of $^{192}$Ir sources

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In the caption to figure 1, ‘3(a)’ and ‘3(b)’ should read ‘1(a)’ and ‘1(b)’, respectively.
A practical implementation of the 2010 IPEM high dose rate brachytherapy code of practice for the calibration of $^{192}$Ir sources

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Abstract
This paper details a practical method for deriving the reference air kerma rate calibration coefficient for Farmer NE2571 chambers using the UK Institute of Physics and Engineering in Medicine (IPEM) code of practice for the determination of the reference air kerma rate for HDR $^{192}$Ir brachytherapy sources based on the National Physical Laboratory (NPL) air kerma standard. The reference air kerma rate calibration coefficient was derived using pressure, temperature and source decay corrected ionization chamber response measurements over three successive $^{192}$Ir source clinical cycles. A secondary standard instrument (a Standard Imaging 1000 Plus well chamber) and four tertiary standard instruments (one additional Standard Imaging 1000 Plus well chamber and three Farmer NE2571 chambers housed in a perspex phantom) were used to provide traceability to the NPL primary standard and enable comparison of performance between the chambers. Conservative and optimized estimates on the expanded uncertainties ($k = 2$) associated with chamber response, ion recombination and reference air kerma rate calibration coefficient were determined. This was seen to be 2.3% and 0.4% respectively for chamber response, 0.2% and 0.08% respectively for ion recombination and 2.6% and 1.2% respectively for the calibration coefficient. No significant change in ion recombination with source decay was observed over the duration of clinical use of the respective $^{192}$Ir sources.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The publication of the 2010 Institute of Physics and Engineering in Medicine (IPEM) code of practice for the determination of reference air kerma rate (RAKR) for high dose rate (HDR) $^{192}$Ir brachytherapy sources provides brachytherapy centres across the UK with a new
methodology for calibrating HDR $^{192}$Ir sources for clinical use (Bidmead et al 2010). It describes a method for calibrating HDR $^{192}$Ir sources that provides direct traceability to the National Physical Laboratory (NPL) primary standard (Sander and Nutbrown 2006). The new code of practice is simpler to set up, has better geometric reproducibility and smaller air kerma calibration coefficient uncertainties when compared to other standard methods (Goetsch et al 1991, Aird et al 1993, Petersen et al 1994, Douysset et al 2005) which relied on interpolation techniques to obtain an air kerma calibration coefficient using a secondary standard.

At The James Cook University Hospital (JCUH), Middlesbrough, the 1993 British Institute of Radiology (BIR)/Institute of Physical Sciences in Medicine (IPSM) working party set of recommendations was used to calibrate HDR $^{192}$Ir sources prior to the adoption of the new code of practice. The recommendations provided a method to measure RAKR using a Farmer chamber/jig combination. It relied on measuring kerma in air with the Farmer chamber and a build-up cap, and making corrections for attenuation, scatter, electron filtration and chamber geometry (Aird et al 1993). It used a calibration method that provided traceability to the primary standard through an external beam secondary standard—a thimble chamber with air kerma calibration coefficient derived from measurements with the chamber in a heavily filtered 280 kV beam at the NPL, but with no jig and no build-up cap. The expanded uncertainties ($k = 2$) of the chamber calibration coefficient associated with this method have been quoted by NPL at 1.2%. However, this is an underestimate as it does not take into account the difference in the NPL calibration setup and the 1993 BIR/IPSM recommended setup. In addition, extrapolating the air kerma calibration coefficient to the effective energy of the HDR $^{192}$Ir source would be expected to increase the total expanded uncertainty to an extent that would be comparable to the 1.1% ($k = 1$) quoted by a recent publication on dosimetric uncertainties for photon-emitting brachytherapy sources (DeWerd et al 2011) which derives its estimate from a calibration setup based on the Goetsch et al (1991) interpolation technique.

The introduction of the NPL primary standard in 2004 resulted in the reduction of air kerma rate coefficient uncertainties through the direct calibration of the HDR $^{192}$Ir source. This meant that the same thimble chamber calibrated against an $^{192}$Ir source which had in turn being calibrated against the NPL primary standard using the 1993 BIR/IPSM setup was seen to have an expanded calibration coefficient uncertainty of 1.1% ($k = 2$). In contrast, the 2010 IPEM code of practice uses a well-type chamber as the instrument of choice due to improved reproducible geometry and smaller expanded chamber calibration coefficient uncertainty of 0.8% ($k = 2$). The benefit of direct traceability to the primary standard is clear given that this is almost a factor 2 smaller than the estimate of 1.2% ($k = 1$) quoted by DeWerd et al (2011) for similar well-type chambers calibrated using the Goetsch et al (1991) interpolation technique.

The 2010 IPEM code of practice recommends a well-type ionization chamber with a brachytherapy source holder/insert to be used as the secondary standard, and a tertiary standard (also known as a field instrument) to be used as an in-house dosemeter for source strength measurements and source stability checks. The tertiary standard can be either another well or a thimble chamber and must be cross-calibrated against the secondary standard. At JCUH, the 2010 IPEM code of practice is implemented through the use of two tertiary standards—a Standard Imaging Plus 1000 well chamber as the first tertiary standard and an NE2571 Farmer chamber as the second tertiary standard, both of which are cross-calibrated against a regional secondary standard.

Whilst it is a straightforward exercise to cross-calibrate a tertiary well standard against the secondary standard, the new code of practice only offers broad advice on how this should be done if using a tertiary standard that is not a well-type chamber. It makes few recommendations regarding the design and use of an alternative ionization chamber/phantom combination, and
Table 1. Equipment used in this study for the determination of reference air kerma rate (RAKR).

<table>
<thead>
<tr>
<th>Instruments</th>
<th>2010 IPEM</th>
<th>1993 BIR/IPSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary standard well chamber</td>
<td>Standard Imaging 1000 Plus (x1)</td>
<td>NE2611 (x1)</td>
</tr>
<tr>
<td>Secondary standard electrometer</td>
<td>PTW Unidos (x1)</td>
<td>PTW Unidos (x1)</td>
</tr>
<tr>
<td>Tertiary standard well chamber</td>
<td>Standard Imaging 1000 Plus (x1)</td>
<td>Farmer NE2571 (x1)</td>
</tr>
<tr>
<td>Tertiary standard electrometer</td>
<td>Standard Imaging CDX-2000 (x1)</td>
<td>NE 2570 (x1)</td>
</tr>
<tr>
<td>Tertiary standard Farmer chamber</td>
<td>Farmer NE2571 (x3)</td>
<td>Farmer NE2571 (x1)</td>
</tr>
<tr>
<td>Tertiary standard Farmer electrometer</td>
<td>NE2570 (x3)</td>
<td>NE 2570 (x1)</td>
</tr>
<tr>
<td>Jig type</td>
<td>Perspex insert in Phantom (x2)</td>
<td>Nucletron in-air jig</td>
</tr>
<tr>
<td>HDR afterloader</td>
<td>Nucletron MicroSelectron V3</td>
<td>Same</td>
</tr>
<tr>
<td>HDR source type</td>
<td>MicroSelectron V2</td>
<td>Same</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>QE Druck DPI142</td>
<td>Same</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Precision PT100</td>
<td>Same</td>
</tr>
</tbody>
</table>

* Not used during this study but included for completeness.

provides no guidance on the magnitude of the uncertainty that would typically be associated with response readings obtained using such a combination.

This paper presents a methodology for deriving the reference air kerma rate calibration coefficient, \( C_{\dot{K}} \), for tertiary standards. To this end, measurements for chamber response and ion recombination, \( K_{\text{ion}} \), were performed over the duration of three HDR \(^{192}\text{Ir}\) source clinical cycles and used in the derivation of \( C_{\dot{K}} \). The results were statistically evaluated to obtain the expanded uncertainties associated with chamber response and \( K_{\text{ion}} \) for all the tertiary standard chambers used in this study with emphasis on the Farmer chambers in the perspex insert/phantom combination. The total expanded uncertainty associated with \( C_{\dot{K}} \) was evaluated in line with recommendations of the International Organization for Standardization (ISO)/Joint Committee for Guides in Metrology (JCGM) working group report on the expression of uncertainties in measurement (JCGM 2008), by combining in quadrature type A uncertainties—standard deviations from the measurement of chamber response and \( K_{\text{ion}} \), and type B uncertainties—manufacturer quotes, equipment calibration certificates and any other assessed uncertainties not derived through direct measurement, of all relevant equipment used in this study. In addition, given the importance of ion recombination with respect to impact on the efficiency of production and collection of charge in ionization chambers, \( K_{\text{ion}} \) was examined for evidence of significant change with source decay over the same period.

2. Methodology

2.1. Equipment

Five ionization chambers, five electrometers, a HDR afterloading unit, temperature and pressure sensors were used for this study and are listed in Table 1. In addition, a 20 × 30 × 12 cm\(^3\) Quality Assurance System for Advanced Radiotherapy (QUASAR) body phantom manufactured by Modus Medical devices Inc., Ontario, Canada, was used in implementing the 2010 IPEM code of practice. The phantom was supplied with a perspex insert to hold the NE2571 Farmer chambers. A second perspex insert to house the source catheter was custom made to fit snugly into the phantom.

The geometry of the inserts was such that when inserted into the phantom, their long axes were parallel to each other and 3.000 ± 0.032 cm centre-to-centre (figure 1(a)). As shown
Table 2. Type B uncertainties \((k = 1)\) associated with all equipment used in this study.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Contributing uncertainty</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUASAR phantom and inserts</td>
<td>Phantom dimension: ± 0.10 mm</td>
<td>± 0.32 mm</td>
</tr>
<tr>
<td></td>
<td>Farmer chamber dimension: ± 0.02 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chamber insert in position: ± 0.01 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catheter insert in position: ± 0.01 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catheter in position: ± 0.01 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Source in position: ± 0.30 mm</td>
<td></td>
</tr>
<tr>
<td>Secondary standard electrometer (PTW Unidos)</td>
<td>Display correction: ± 0.1%</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>Tertiary standard electrometer (Standard Imaging CDX-2000)</td>
<td>Linearity: ± 0.05%</td>
<td>± 0.05%</td>
</tr>
<tr>
<td>Tertiary standard Farmer electrometer ((\times 3))</td>
<td>Linearity: ± 0.05%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Display resolution: ± 0.05%</td>
<td>± 0.06%</td>
</tr>
<tr>
<td></td>
<td>Timer resolution: ± 0.003%</td>
<td></td>
</tr>
<tr>
<td>Well chamber calibration coefficient</td>
<td></td>
<td>± 0.8%</td>
</tr>
<tr>
<td>Farmer chamber calibration coefficient</td>
<td></td>
<td>± 1.1%</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>± 0.01% of full scale</td>
<td>± 0.02%</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>±0.2 °C</td>
<td>± 0.12%</td>
</tr>
</tbody>
</table>

* Taken from NPL calibration certificate or estimate. All other estimates were obtained from manufacturer quotes.

In Table 2, the total uncertainty associated with this setup is dominated by the uncertainty in source position in the catheter.

The uncertainty of 0.032 cm in the distance between the inserts meant that given the Farmer chamber sensitive volume of 2.4 cm axial length, the radial distance of a source stepping alongside the chamber volume had a maximum length of between 3.817 and 3.867 cm. This was expected to have a dosimetric impact equivalent to a maximum absolute change of 0.02%, 0.08% and 0.18% in radial dose, anisotropy and geometry functions, respectively, which when combined in quadrature was observed to be within the estimated total treatment planning system interpolation uncertainty of 2.6% quoted by DeWerd et al. (2011).

The uncertainty in radial distance of the source stepping alongside the chamber volume is also relevant in light of the well-documented correlation between scatter contributions and phantom size/dimensions in brachytherapy source strength measurements (Venselaar et al. 1996, Karaiskos et al. 1998). With respect to HDR 192Ir source strength measurements, other studies have also reported changes of 1% and 4% in the radial dose function at radial distances of 2.5 and 5 cm, respectively, in cylindrical water phantoms with dimensions of 18 cm \(\times\) 18 cm (diameter \(\times\) length) when compared to an unbounded water phantom (Pérez-Calatayud et al. 2004, Granero et al. 2008). Similarly, for a cylindrical phantom with dimensions 28 cm \(\times\) 28 cm, the same studies reported changes in the radial dose function of 0.5% and 2.5%, respectively. Consequently, it was assumed that given the geometry of the inserts in the QUASAR phantom—effectively a 20 cm \(\times\) 12 cm cylinder with an additional
A practical implementation of the 2010 IPEM HDR brachytherapy code of practice

Figure 1. Figure 3(a) shows the Perspex inserts housing the NE2571 Farmer chamber and a 6-French Intralumenal source catheter, while figure 3(b) shows the alignment of inserts and the Farmer chamber. The source catheter insert was designed to fit in one direction only. A black line was scribed into the face of both inserts to enable alignment of the chamber with the inserts. The insert housing the NE2571 Farmer chamber was 2.0 cm in diameter and 19.6 cm in length with the chamber extending 8.8 cm into it. The insert housing the source catheter was 2.0 cm in diameter and 13.6 cm long with the catheter extending 9.0 cm into it and corresponding to a position 4.2 cm proximal from the tip of the Farmer chamber.

5 cm of perspex laterally on either side of the central axis, it was unlikely that the changes in the radial dose function would be significant.

In addition, by making sure that the inserts fitted snugly into the phantom and were aligned with the Farmer chamber as shown in figure 1(b), this resulted in a setup that was reproducible to within 0.32 mm (1.1%) orthogonal to the direction of motion of the source. When combined with the regular monthly quality assurance performed on the HDR afterloading unit at JCUH to ensure that the source positional accuracy remained within the manufacturer specified tolerance of ±1 mm in the direction of motion of the source, this had the dual effect of minimizing source position uncertainties and ensuring that uncertainties in dose rates remained within acceptable limits.

Since the 2010 IPEM code of practice does not specify a recommended position of Farmer chamber response measurement, two source catheter inserts were used for this study. The first insert allowed the source catheter to extend 6.0 cm into the insert with the tip corresponding to a position 1.2 cm proximal from the tip of the Farmer chamber. The second insert was identical to the first with the exception that the source catheter extended an additional 3 cm into the insert with the tip corresponding to a position 4.2 cm proximal from the tip of the Farmer chamber (illustrated in figure 1(a)). The two inserts provided different coverage of the Farmer chamber sensitive volume as illustrated in figure 2. The additional coverage of the second insert enabled the determination of the position of maximum chamber response—the ‘sweet spot’. Given that the response varied slowly, within 0.5% over 5 mm about the sweet spot and in the direction of motion of the source, measurements with this insert were used to derive optimized estimates for chamber response and $K_{ion}$ associated with the Farmer NE2571 chambers that were used in this study. This was in contrast to the first insert which was used to derive conservative estimates because it only enabled measurements to be carried out on the shoulder of the response curve where the response was observed to vary significantly, i.e. within 2.5% over 2.5 mm in the direction of motion of the source.
2.2. Determination of RAKR

At JCUH, the 2010 IPEM code of practice was initially implemented alongside the 1993 BIR/IPSM recommendations. This was done to provide a basis for comparison and to ensure a smooth transition between both methods. The methodology for determination of RAKR with a tertiary standard in line with the old and new sets of recommendations will be reviewed here briefly for completeness. The implementation of both sets of recommendations takes the form of first cross-calibrating the tertiary standard against the secondary standard to determine an inter-comparison factor so as to ensure traceability to the NPL primary standard. This is followed by the verification of the source RAKR with the secondary standard and finally the derivation of an RAKR calibration coefficient (called $C_\dot{K}$ in this study) to convert the tertiary standard response reading into RAKR. A summary of the formulae used to quantify RAKR using both sets of recommendations is listed in table 3. A setup procedure that can be used to cross-calibrate a tertiary standard against a secondary standard in conformance with both sets of recommendations is illustrated in figure 3.

With respect to the 1993 BIR/IPSM recommendations, a Nucletron in-air jig is set up as shown in figure 3(a). A secondary standard NE2611 thimble chamber is inserted into a perspex holder and aligned such that it is equidistant from two parallel catheter tubes placed on either side so that the source-to-chamber distance is 10 cm. The source is sent out in each tube to this point for a dwell time of 300 s. The chamber is then interchanged with the tertiary standard Farmer chamber and new response readings taken under the same exposure conditions. This process is repeated three times to give six response readings for either chamber. The ratio of the mean of the readings is then used to derive an inter-comparison factor, $\bar{M}_S/\bar{M}_T$, where $\bar{M}_S$ is the mean response reading with the secondary standard chamber in position and $\bar{M}_T$ the mean reading with the tertiary standard chamber in place.

With respect to the 2010 IPEM code of practice, the cross-calibration measurements for the tertiary standard well chamber against the secondary standard well chamber is preceded by determining the sweet spot of both chambers. This is done by sending the source out in steps of 2.5 mm until the point of maximum response is detected. After determining the sweet spot, the source is then sent out to both chambers for an arbitrary fixed dwell time (dwell times of 30 s are used at JCUH). With respect to the cross-calibration of a tertiary standard Farmer chamber against a secondary standard well chamber, the setup which is currently in use at
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Table 3. Formulae used for determination of reference air kerma rate (RAKR) using the secondary and tertiary standards under the 2010 IPEM and 1993 BIR/IPSM recommendations.

<table>
<thead>
<tr>
<th>2010 IPEM</th>
<th>1993 BIR/IPSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary standard</td>
<td>Tertiary standard</td>
</tr>
<tr>
<td>M \cdot K_{ions} \cdot N_{ks} \cdot F_{T,P}</td>
<td>C_{KA} \cdot M \cdot F_{T,P}</td>
</tr>
<tr>
<td>Secondary standard</td>
<td>Tertiary standard</td>
</tr>
<tr>
<td>M \cdot N_{ks} \cdot F_{T,P} \cdot F_{X}</td>
<td>C_{KB} \cdot M \cdot F_{T,P}</td>
</tr>
</tbody>
</table>

- **M** = Uncorrected chamber response reading
- **K_{ions}** = Chamber ion recombination factor for the secondary standard
- **N_{ks}** = Chamber calibration coefficient
- **F_{T,P}** = Temperature and pressure correction factor
- **C_{KA}** = Tertiary standard reference air kerma rate calibration coefficient defined by \( \frac{M}{MT} \cdot K_{ions} \cdot N_{ks} \), where \( \frac{M}{MT} \cdot K_{ions} \) is the inter-comparison factor between secondary and tertiary standards, and \( K_{ions} \) is the chamber ion recombination factor for the tertiary standard
- **F_{X}** = Total correction factor for scatter produced by the Nucletron in-air-jig, dose gradient, electron filtration of build-up cap and inverse square as described in Aird *et al.* (1993)
- **C_{KB}** = Tertiary standard reference air kerma rate calibration coefficient defined by \( \frac{M}{MT} \cdot N_{ks} \), where \( \frac{M}{MT} \) is the inter-comparison factor between secondary and tertiary standards

JCUH is illustrated in figure 3(b). The source is sent out to the sweet spot of the well chamber for a dwell time of 30 s. Since the code of practice gives no recommended dwell time for the Farmer chamber, a dwell time of 60 s was used. This enabled the collection of charge that was equivalent to at least 0.25 of a Gray scale unit on the Farmer NE2570 electrometers over the duration of the source clinical cycle. Also, since the code of practice gives no recommended dwell position for the Farmer chambers two source catheter insert geometries were used in this study. In the first geometry, the source was sent out to the end of the intraluminal catheter.

Following the observation of significant variation in Farmer chamber response, the insert was redesigned to give the second geometry which enabled the source to be sent to the sweet spot of the chamber.

2.3. Determination of the RAKR calibration coefficient

The RAKR calibration coefficient, \( C_{K} \), for the tertiary standards was obtained using

\[
C_{K} = \left[ \frac{M_{S}}{M_{T}} \cdot \frac{K_{ions}}{K_{ions}} \right] \cdot N_{ks} \cdot F_{T,P} \cdot F_{elec} \cdot F_{decay},
\]

where \( M_{S} \), \( K_{ions} \), and \( M_{T} \), \( K_{ions} \) denote the response and ion recombination associated with the secondary and tertiary standard chambers, respectively. \( N_{ks} \), \( F_{T,P} \), \( F_{elec} \) and \( F_{decay} \) denote the chamber calibration coefficient, temperature, pressure, electrometer and source decay corrections, respectively. For the purposes of this study the chamber responses were obtained and collated over the clinical lifetime of three successive \(^{192}\)Ir sources, i.e. a 9 month period,
Figure 3. Figure 3(a) shows the cross-calibration set up under the 1993 BIR/IPSM set of recommendations using the Nucletron in-air-jig and MicroSelectron v3 afterloader, while figure 3(b) shows the same process under the 2010 IPEM code of practice using a well-Farmer chamber combination with the same afterloader.

and each with a half-life of 73.83 days. The two source catheter inserts were used for separate source cycles. The first tertiary standard Farmer chamber, denoted in this report as Farmer\(^1\), was used for measurements with the first source catheter insert only, i.e. over the first \(^{192}\)Ir source cycle in the period August–October 2010. The second tertiary standard Farmer chamber, denoted as Farmer\(^2\), was used for measurements with both inserts, i.e. over all three source cycles in the period August 2010–April 2011, while the third tertiary standard Farmer chamber, denoted as Farmer\(^3\), was used with the second insert only, i.e. over the second and third source cycles in the period November 2010–April 2011. The secondary and tertiary standard well chambers, denoted as Well\(^1\) and Well\(^2\), respectively, were used over the first and second source cycles only.

In addition, the responses were corrected for pressure, temperature and source decay. This was done to normalize all response readings to the time of calibration of the source in order to facilitate the statistical evaluation of the chamber response variation within each source cycle and across all three source cycles. At each measurement session, at least five response readings were taken with the chamber bias set to full and half voltages, respectively. The temperature was taken prior to each response measurement, while the pressure was taken at the start of each full- and half-voltage response measurement cycle. Also, after each cycle of at least five chamber response measurements at full and half voltages, respectively, an additional three response readings at full voltage were obtained, the mean of which was compared to the mean of the preceding five full voltage readings to identify any drift in electrometer response.
Table 4. Summary of expanded uncertainties ($k = 2$) of chamber response, $K_{\text{ion}}$, and RAKR calibration factor, $C_{\text{K}}$. The numbers in brackets refer to the number of measurements performed in deriving the respective uncertainty.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Expanded uncertainty of chamber response (%)</th>
<th>Expanded uncertainty of $K_{\text{ion}}$ (%)</th>
<th>Total expanded uncertainty of $C_{\text{K}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well$^1$</td>
<td>0.2 (67)</td>
<td>0.04 (40)</td>
<td>0.9$^a$</td>
</tr>
<tr>
<td>Well$^2$</td>
<td>0.3 (149)</td>
<td>0.05 (100)</td>
<td></td>
</tr>
<tr>
<td>Farmer$^1$</td>
<td>First insert</td>
<td>Second insert</td>
<td>First insert</td>
</tr>
<tr>
<td></td>
<td>2.3 (75)</td>
<td>0.17 (70)</td>
<td>2.6$^a$</td>
</tr>
<tr>
<td>Farmer$^2$</td>
<td>1.9 (75)</td>
<td>0.4 (42)</td>
<td>0.20 (70)</td>
</tr>
<tr>
<td>Farmer$^3$</td>
<td>0.3 (65)</td>
<td>0.04 (9)</td>
<td>1.2$^a$</td>
</tr>
</tbody>
</table>

$^a$ The total expanded uncertainty was determined by combining in quadrature the type A expanded uncertainties of the chamber response and $K_{\text{ion}}$, with type B uncertainties of the remaining terms in equation (1) as described in section 2.3.1.

All Farmer chamber response measurements were carried out with the Farmer electrometer sensitivity set to low range. Whilst no Farmer electrometer corrections were applied to the Farmer response readings given that the chambers were cross-calibrated against the secondary standard and hence inherited the corrections made to the secondary standard chamber response readings, the type B uncertainties associated with the electrometers were used to provide conservative estimates of $C_{\text{K}}$. The same was also applied to the tertiary standard well chamber.

Uncorrected chamber response measurements were used to account for the effect of ion recombination by quantifying an ion recombination factor, $K_{\text{ion}}$, using

$$K_{\text{ion}} = \left( \frac{I_2V_1^2 - I_1V_2^2}{I_2V_1^2 - I_2V_2^2} \right)^{-1},$$

(2)

where $I_1$ and $I_2$ are the chamber responses at polarizing voltages $V_1$ and $V_2$, respectively (Attix 1984). For $V_1 = 2V_2$, equation (2) reduces to

$$K_{\text{ion}} = \left( \frac{4}{3} - \frac{I_1}{3I_2} \right)^{-1}.$$

(3)

The nominal full polarizing voltage was set to 300 V for the well chambers and 250 V for the Farmer chambers.

Given that the decay of the source would result in a reduction in source activity and hence RAKR with time, it was unclear what impact this would have on $K_{\text{ion}}$ over the clinical lifetime of the source. Consequently, $K_{\text{ion}}$ for the well and Farmer chambers was examined for evidence of change over the clinical lifetime of the source.

The displayed polarizing voltage for the Farmer chambers deviated from the nominal value of 250 V. It was observed to be 245.04 ± 0.49 V. The same effect was also observed at half voltage with the displayed half voltage varying from the 50% value by 0.27 ± 0.06%. This meant that clearly $V_1 \neq 2V_2$. The effect of this fluctuation was evaluated by comparing the change in $K_{\text{ion}}$ when computed under the assumptions $V_1 \neq 2V_2$ and $V_1 = 2V_2$ using equations (2) and (3), respectively.

2.3.1. Determination of uncertainties. The total expanded uncertainty associated with $C_{\text{K}}$, summarized in table 4, was evaluated by combining in quadrature the type A and/or type B uncertainties (table 2) associated with all the terms in equation (1) with the exception of $F_{\text{decay}}$. 
The expanded uncertainties associated with $M_S$, $K_{ionS}$ (Well1) and $M_T$, $K_{ionT}$ (Well2, Farmer1,2.3) were classified as type A uncertainties and obtained from measurement by statistical evaluation of the weighted response variance per measurement session per source cycle. The respective uncertainties were obtained using

$$S_j^2 = \frac{1}{N - 1} \left[ \sum_{i=1}^{N} X_{i,j}^2 - N \mu_j^2 \right],$$  \hspace{1cm} (4)

where $j$ is the measurement session and $N$, $X$ and $\mu$ are the number of measurements per measurement cycle, chamber response value and mean response, respectively. The average variance, $S_{ave}^2$, over multiple source cycles was evaluated using

$$S_{ave}^2 = \left[ \sum_{j=1}^{K} W_{j,k} \cdot S_j^2 \right],$$ \hspace{1cm} (5)

where $K$ is the number of source cycles and $W_{j,k}$ is a weighting factor that assigns a weight to each source cycle equal to the ratio of number of measurement sessions in the cycle to the total number of measurement sessions in the combined cycles. The purpose of the weighting factor was to minimize any potential underestimation that could arise from combining unequal number of measurement sessions across the cycles. Equation (4) was used to statistically evaluate Farmer1 chamber measurements, while equations (4) and (5) were used for Farmer2,3 and Well1,2 chamber measurements.

The uncertainties associated with $N_\dot{K}_S$, $F_{elec}$ and $F_{T,P}$ were classified as type B uncertainties and were obtained from calibration certificate estimates and manufacturer quotes (table 2). $N_\dot{K}_S$ was assumed to have uncertainties of 0.8% for Well1,2 and 1.1% for Farmer1,2,3, respectively, in line with NPL quotes. $F_{elec}$ was assumed to be 0.1% for Well1, 0.05% for Well2 and 0.06% for Farmer1,2,3, respectively, in line with NPL calibration certificate estimates and manufacturer quotes.

3. Results and discussion

3.1. Chamber response

The variation in mean response per measurement session for all the chambers is shown in figures 4(a) and (b). The points were normalized to the overall mean of the total response measurements in the respective source cycle to enable direct comparison across the source cycles. The mean response of Farmer1 was observed to vary by as much as 2.0%. Farmer2 was observed to vary by as much as 1.5% when using the first insert and 0.3% with the second insert, whilst for Farmer3 it was 0.2%. The mean response for both well chambers on the other hand varied by 0.2%.

The significant variability in the mean response exhibited by the Farmer chambers when using the first insert was due to the inadequate coverage of the chamber response curve. This was in contrast to measurements performed with the second insert which provided adequate coverage and ensured that contributions to response uncertainty from positional uncertainties were effectively minimized. The results summarized in table 4 show a conservative estimate of Farmer chamber response expanded uncertainty ($k = 2$) of 2.3% when using the first insert and an optimized estimate of 0.4% when using the second insert.

The test for electrometer drift was performed using measurements obtained with both inserts and showed the measured drift to be insignificant. When using response measurements obtained with the first insert, Farmer1 was seen to have an average drift of 0.14 ± 0.15%, while...
3.2. $K_{\text{ion}}$

The variation in the mean $K_{\text{ion}}$ followed a similar trend to that observed for the chamber responses, and is illustrated in figures 6(a) and (b) with the Farmer chambers showing the largest variability when measurements were carried out using the first insert. The mean $K_{\text{ion}}$ for Farmer$^{1,2}$ varied by as much as 0.06% and 0.13%, respectively, from an overall mean of...
1.0009 and 1.0015, respectively, when using the first insert. When using the second insert, the mean $K_{\text{ion}}$ for Farmer$^2$ varied by 0.03% and 0.02%, respectively, from an overall mean of 1.0009 and 1.0008. With respect to the well chambers, it varied identically by 0.02% from an overall mean of 1.0006 for both chambers. The expanded uncertainties are summarized in table 4. They show the benefit of performing measurements at the sweet spot for the Farmer chambers with the expanded uncertainty ($k=2$) reducing from 0.2% to 0.08%. As expected, the well chambers performed better with uncertainties of 0.05%.

A linear regression test performed on $K_{\text{ion}}$ showed no evidence of a correlation between change in $K_{\text{ion}}$ and reduction in source activity resulting from source decay. Farmer$^1$ and Farmer$^2$ were observed to have an $R^2$ of 0.513 and 0.025, respectively, for measurements with the first insert. When using the second insert, $R^2$ was observed to be 0.299 for Farmer$^2$. There were insufficient data points to obtain $R^2$ for Farmer$^3$. Given that for all the chambers, the variation of $K_{\text{ion}}$ from the overall mean within a given source cycle was within the expanded uncertainties, this led to the conclusion that $K_{\text{ion}}$ does not change significantly with source decay. In other words, $K_{\text{ion}}$ can be assumed to be constant with source decay.

Fluctuations in the full and half polarizing voltages applied across the chambers were seen to have negligible impact on $K_{\text{ion}}$. Similar to the test for electrometer drift, the impact was evaluated using measurements performed with both inserts. When using the first insert, the mean change in $K_{\text{ion}}$ for Farmer$^1$ was seen be $-0.001 \pm 0.001\%$, while for Farmer$^2$ it was $-0.002 \pm 0.001\%$ (figure 7(a)). Whilst these numbers are smaller than the measured expanded uncertainties of 0.17% and 0.20%, respectively, a linear regression test performed on the data points showed a finite trend in the value of $K_{\text{ion}}$. However, this appears insignificant given that it occurs well within the measurement uncertainty bounds. Figure 7(b) validates this assumption with an $R^2$ of 0.009 and mean change of 0.001 ± 0.000% for Farmer$^2$ when the test was performed with the second insert. There were insufficient data points to make an assessment for Farmer$^3$.

3.3. RAKR calibration coefficient

The 1993 BIR/IPSM and 2010 IPEM sets of recommendations gave similar levels of accuracy with respect to the measurement of RAKR—within ±1% of each other and 2% of the source certificate value. The former, however, showed marginal increase in measurement...
uncertainty as expected. With respect to $C_k$ for the Farmer chambers, the benefit of performing measurements at the sweet spot is illustrated in table 4 with the total expanded uncertainty ($k = 2$) reducing from 2.6% (conservative estimate) to 1.2% (optimized estimate). The optimized estimate is comparable to 0.9% that was obtained for the well tertiary standard.

4. Conclusion

This report arrives at a number of conclusions. The 2010 IPEM code of practice is simple to implement. When compared to the 1993 BIR/IPSM set of recommendations it is quicker and less cumbersome. It can be implemented with equal ease when using either a well-type or Farmer NE2571 chamber as tertiary standards. When used with an appropriate reproducible phantom/insert geometry, the Farmer NE2571 chambers can be used to measure RAKR with an uncertainty that is only marginally greater than well chambers. However, the phantom/insert geometry must be such that it enables response measurements to be performed at the position of maximum response—the sweet spot. Conservative estimates of uncertainties associated with the RAKR calibration coefficient, $C_k$, have shown that even in the event that measurements are not performed at the Farmer chamber sweet spot, the measured RAKR is unlikely to deviate from the source certificate RAKR value by more than 3%—the investigative action level recommended by the code of practice. With respect to $K_{ion}$, no significant change was observed over the clinical lifetime of the HDR $^{192}$Ir source. In other words, $K_{ion}$ can be assumed to be constant over the clinical lifetime of the source. In addition, fluctuations in the full and half polarizing voltages across the chambers can be ignored given that they remain within the measurement uncertainty limits of $K_{ion}$.

References


Attix F H 1984 Determination of $A_{ion}$ and $P_{ion}$ in the new AAPM radiotherapy dosimetry protocol Med. Phys. 11 714–6


Pérez-Calatayud J, Granero D and Ballester F 2004 Phantom size in brachytherapy source dosimetric studies Med. Phys. 31 2075–81


Sander T and Nutbrown R F 2006 The NPL air kerma primary standard TH100C for high dose rate 192Ir brachytherapy sources NPL Report DQL-RD 004 (Teddington: NPL) http://publications.npl.co.uk