3D Printed Brachytherapy Jig for Reference Air Kerma Rate Calibration

Emily Simpson-Page (Emily.Simpson-Page@health.qld.gov.au)
RBWH: Royal Brisbane and Women's Hospital https://orcid.org/0000-0002-5262-6465
Lynsey Hamlett
Sunshine Coast University Hospital
Dominika Lew
Genesis Cancer Care Queensland
Holly Stephens
Genesis Cancer Care Queensland
Rachael Wilks
Royal Brisbane and Women's Hospital
Tanya Kairn
Royal Brisbane and Women's Hospital
Scott B Crowe
Royal Brisbane and Women's Hospital

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Emily Simpson-Page · Lynsey Hamlett · Dominika Lew · Holly Stephens · Rachael Wilks · Tanya Kairn · Scott B. Crowe

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Abstract 3D printing in modern radiotherapy provides creative autonomy which can be a valuable tool for use in brachytherapy source calibration. Radiotherapy centres may verify their brachytherapy source strength with a calibrated Farmer chamber. For this purpose, a jig was designed, 3D printed and commissioned for in-air source strength calibration. Measurements on four afterloaders with varied equipment and environments were completed. A full uncertainty budget was developed and measurements with the in-air jig were consistently within 3% of the certificate source strength. By creating a jig that is able to be customised to multiple catheter sizes and cylindrical chamber designs, centres can be provided with the option of independently checking their source strength with ease and for little cost.

E. Simpson-Page
Cancer Care Services, Royal Brisbane and Women's Hospital, Herston, Qld, Australia
E-mail: emily.simpsonpage@gmail.com

L. Hamlett
Sunshine Coast University Hospital, Sunshine Coast, Qld, Australia

D. Lew and H. Stephens
Genesis Cancer Care Queensland, Auchenflower, Qld, Australia

R. Wilks
Cancer Care Services, Royal Brisbane and Women's Hospital, Herston, Qld, Australia
and School of Information Technology and Electrical Engineering, University of Queensland, St. Lucia, Qld, Australia
and Herston Biofabrication Institute, Metro North Hospital and Health Service, Herston, Qld, Australia

T. Kairn and S.B. Crowe
Cancer Care Services, Royal Brisbane and Women's Hospital, Herston, Qld, Australia
and School of Information Technology and Electrical Engineering, University of Queensland, St. Lucia, Qld, Australia
Herston Biofabrication Institute, Metro North Hospital and Health Service, Herston, Qld, Australia
and School of Chemistry and Physics, Queensland University of Technology, Brisbane, Qld, Australia

Keywords Radiation therapy · Iridium-192 · additive manufacture · fused deposition modelling

Introduction

Radiotherapy centres that provide brachytherapy treatments should have the ability to independently verify the source strength provided by the manufacturer [1]. The International Atomic Energy Agency (IAEA) recommends this verification use reference air kerma rate (RAKR) to specify the activity of gamma sources [2]. A number of different detector types are able to undertake this calibration though most often a well chamber is used [3,4]. In many countries, centres are required to ship well chambers overseas for calibration, since not all local standards laboratories maintain a brachytherapy standard or provide a well chamber calibration service [5].

Because the source strength is directly related to the dose received by a patient it is prudent to have an independent dosimetry system to check against and verify the primary method for calibration. Further to this, having an independent dosimetry system for a brachytherapy source can aid with establishing a mean ratio between the locally measured and vendor specified source strengths which can function as an early indication of problems with the calibration system [6]. Moreover, when sending well chambers overseas for calibration, centres may experience a period of time where they do not have a dosimetry system for calibrating brachytherapy sources. The ability to use a traceable calibrated Farmer chamber provides an easy solution to both challenges; the Farmer chamber can be used both to verify the well chamber measurement and to provide source calibration checks when the well chamber is not available. This method is in accordance with IAEA recommendations for using a cylindrical chamber, such as a Farmer chamber, to calibrate a brachytherapy source [2].

Where primary standards laboratories are able to calibrate cylindrical chambers at energies either side of the Ir-192 mean energy, a correction factor can be produced for Ir-192 by interpolation. This approach is recommended by the IAEA [2]. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), for example, is able to calibrate cylindrical chambers for reference photon dosimetry in beam qualities 250 kV and Co-60 gamma rays. An interpolation between these energies can then be used to calculate an estimate for the N_k correction for Ir-192, which decays via gamma decay with an average energy of 397 keV [2].

Using the interpolated N_k correction for Ir-192, the IAEA formalism can be followed for calculation of RAKR. This formalism defines RAKR at a distance of 1 m. This 1 m measurement in not always practical due to low signal and possible high leakage currents of ionisation chambers used. According to the IAEA formalism [2], the RAKR can be determined from measurements with a cylindrical chamber at a recommended optimal distance of 16 cm.

Use of the IAEA formalism in conjunction with a calibrated Farmer chamber is subject to increased uncertainties in comparison with well chamber measurements [4, 7, 8]. When using a cylindrical chamber in-air to calibrate a brachytherapy source, errors can manifest in the way of set up reproducibility, scatter corrections, air attenuation factors and source-to-chamber positional accuracy. These errors and uncertainties can be accounted for and minimised with a reproducible and robust set up.

The use of jigs to enable reproducible Farmer chamber measurements has been investigated previously, using both commercially available [9, 10] and in-house designed devices [4, 7]. However, although the use of 3D printed jigs for non-reference brachytherapy dosimetry has recently been reported in the literature [11], none of these examples have utilised a 3D printed jig for the purpose of absolute dose measurements for a brachytherapy source using the IAEA protocol.

3D printing in radiotherapy is a useful tool for optimising clinical practice and workflow [11–14]. The speed and accuracy with which jigs can be printed are desirable for radiotherapy departments, particularly those that already have a 3D printing programme set up. This use of 3D printing to address a clinical need provides a quick, cheap and effective solution to alternative jigs available for brachytherapy in-air calibration.

By characterising components of the in-air calibration method to a high level of precision, brachytherapy centres can achieve a reliable measurement of the RAKR of brachytherapy sources without compromising accuracy. The ability to independently verify the strength of a brachytherapy source provides a quality assurance and external audit check which is an important aspect of quality radiation delivery. For this reason, it is necessary for a locally fabricated jig to be tested in various contexts and with changing equipment to ensure reproducible and reliable results.

The objective of this study was to design and fabricate an in-air jig using 3D printing methods, characterise all associated uncertainties and perform repeat measurements for different Ir-192 brachytherapy delivery systems, to evaluate the reliability and robustness of the 3D printed RAKR jig.

Method

Design and fabrication of 3D printed jig

The jig was designed to be customisable for use in different radiotherapy centres, allowing for various brachytherapy afterloaders, catheters, cylindrical chambers and measurement methods. The pieces that held the chamber and catheters were all able to be interchanged with counterparts of various sizes, so that a variety of chambers and catheters could be accommodated with the same base frame. The cavities for holding the catheters and chamber were defined using known dimensions published by vendors with suitable tolerances added. Tolerances were optimised based on a series of test prints, whereby an iterative approach to determine the most reproducible and appropriate dimensions for equipment to fit was completed.

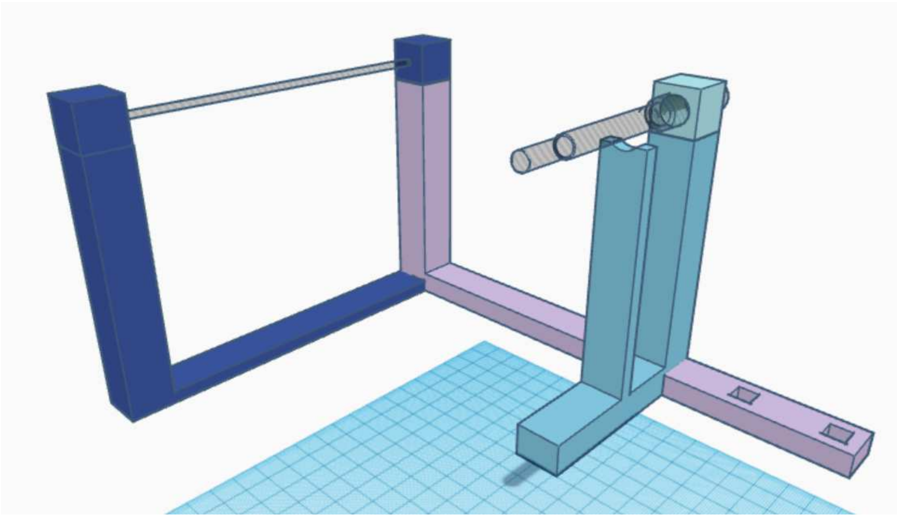

Fig. 1 Tinkercad design of RAKR measurement jig, showing location of source catheter (grey object between dark blue supports) and location of ionisation chamber (grey object on light blue supports, shown without build-up cap for clarity)

The jig, shown in figure 1, was designed in Tinkercad and printed with 1.75 mm polylactic acid (PLA) filament on a Raise 3D Pro 2 dual extrusion printer (Raise 3D Technologies, Irvine, USA), using the settings listed in table 1. To reduce scatter, PLA support structures were only introduced when required. For local testing, the jig was initially created for use with a PTW 30013 Farmer chamber (PTW, Freiburg, Germany) and 2 mm diameter, plastic interstitial needle. The design and fabrication process was then repeated for three additional catheter sizes.

For a combination of Ir-192 sources and Farmer type chambers, the optimal RAKR measurement distance has been shown to be 16 cm, though measurement distances should be selected between 10 and 40 cm [2]. The main jig was designed so that the chamber could sit at three distances from the source; 16, 20 and 24 cm. This allows repeated measurements to determine source strength from different distances. An attachment for the jig was also created to allow for measurements using a seven-distance scatter estimate. This provided a further four positions for the chamber to sit at 30, 34, 38 and 42 cm from the source.

Table 1 Print settings for RAKR In-Air Jig

Setting	
Infill Density	10 %
Shells	3
Layer Height	0.3 mm
Material	1.75 mm PLA
Total Print Time	11 hrs
Filament Amount	170.5 g
Cost	$ 5.12

In-house uncertainty evaluation for 3D printed jig

After completion of 3D printing of the initial version of the jig (for PTW Farmer chamber and 2 mm needle), a visual inspection of the parts was performed and physical measurements of dimensions were made. Testing included assessment of geometric accuracy using calipers, assessment of fit for various needles and the PTW 30013 Farmer chamber, as well as the fit of the support arm and robustness of connections. Gentle manual manipulation was used to ensure the jig did not separate when weight was placed on joints. This was completed to ensure that when the source moves in and out through the catheter, the jig would not deform or separate. Connections that were slightly loose due to printer tolerances could be tightened using adhesive tape and connections that were too tight could be adjusted by filing.

Although the jig was printed with a comparatively low in-fill density (see table 1), the proximity of jig components to both the chamber and the source (see figure 1) made it important to establish the potential for scatter from the jig to affect the RAKR measurement. This test was performed by comparing scatter correction factors calculated with and without inclusion of jig scatter effects. A scatter correction without jig effects was calculated using Chang et al's empirical scatter estimate [15,16], which assumes that scatter comes from the surfaces bounding the room in which the measurement is made (walls, ceiling, floor) and therefore relies on the room dimensions to calculate the scatter correction. Scatter corrections that take jig scatter into account (along with wall, ceiling, floor and other sources of scatter in the room) were evaluated using physical measurements at several set distances from the source. Specifically, additional data was measured for seven distances as per IAEA formalism, by using the purpose-designed extension to the jig which allows seven positions for the source to chamber distance. The seven distance measurement data were analysed by developing a python script using SciPy [17] that used an established least squares method [18,19] to derive a constant from the relationship between primary and scattered contributions to the total integrated charge measurement [20]. A two distance estimation of scatter was also performed, per Butler et al. [9], as a secondary verification of the potential magnitude of jig scatter.

As part of the local preliminary testing process, an uncertainty budget for the jig was developed from guidelines in IAEA TECDOC 1585 and uncertainty budgets that have previously been included in brachytherapy literature [21, 22]. TECDOC 1585 [23] provides guidance to standards laboratories regarding the assessment and reporting of uncertainty in measurements with reference to the ISO/IEC Guide 98-3:2008, colloquially referred to as the ISO-GUM method [23, 24]. The TECDOC 1585 document provides an example of uncertainty analysis for RAKR calibrations which was used as a template to begin the uncertainty analysis used in this study [23]. Sources of uncertainty were initially broken down with reference to the IAEA in-air RAKR formalism described in the next section (see equation 1).

Uncertainty in N_K was taken from published uncertainties from derivation of N_k for Ir-192 [25]. For this uncertainty contribution and for Type B uncertainties presented in this study, effective degrees of freedom were assigned in accordance with suggestions from IAEA TECDOC 1585 [26]. Repeated inhouse measurements using a GammaMed Plus HDR brachytherapy unit (Varian Medical Systems, Palo Alto, USA) were used to estimate Type A uncertainties for influence quantities such as temperature and pressure, while Type B uncertainties were derived from the resolution on the measurement devices used during the experimental measurements. The uncertainty in the measured integrated charge consisted of Type A and Type B uncertainties taken from data collected and calibration certificates for the chamber and electrometer used in this study. The error for time in the expression was taken from published errors in published Varian GammaMed plus specifications, which was verified during commissioning, for the accuracy in dwell time resolution. The uncertainty for the k_{air} factor was derived from TECDOC 1274 [2]. Because the scatter was derived empirically, the published uncertainties were included [15]. The Kondo-Randolph [27] and [28] tables were used to calculate k_n which included an anisotropy factor $A_{KR,pn}$, isotropic factor $A'_{pn(r)}$ and an A_w factor correcting for the material of the inner wall of the chamber. The A_w factor was taken from the IAEA TECDOC 1274 [2] values for the PTW 30001 chamber. These values were chosen as they had been used previously for the PTW 30010 chamber [9] and the PTW3 0013 farmer chamber has the same build up cap and wall material as its non waterproof counterpart. The individual uncertainty for each of these components contributed to the overall uncertainty for k_n.

In order to asses the total uncertainty affecting comparisons between RAKR measurements made with a Farmer chamber in the 3D printed jig and RAKR measurements made using a well chamber, an assessment of the total uncertainty for the well chamber was also required. This assessment also accounted for Type A and B uncertainties, while appreciating that there was no contributing error for air attenuation, significant scatter contributions, extensive position uncertainties and k_n chamber corrections. Polarity and recombination were not corrected for for the well chamber measurements as the polarity and bias settings quoted on the calibration certificate were used for measurements.

Multi-centre measurements of RAKR with 3D printed jig

Table 2 Equipment details for testing of in-air jig reliability

Afterloader Model	Serial Number	Farmer Chamber	Well Chamber	Catheter
GammaMed Plus HDR	H641123	PTW 30013	PTW33005	Plastic interstitial Needle GM11007580
GammaMed Plus PDR	H641124	PTW 30013	PTW33005	Plastic interstitial Needle GM11007580
Flexitron HDR	FT00594	PTW 30013	SI HDR 100 Plus	Proguide Sharp needle 6F 089.939
Flexitron HDR	FT00668	PTW 30013	PTW 077092	Proguide Sharp needle 6F 189.067

In order to verify the reliability of RAKR measurements made using the 3D printed jig in a small range of clinically-likely conditions, the jig was used to perform in-air measurements of RAKR using four different Ir-192 delivery systems in three different brachytherapy centres, with results compared to reference well chamber measurements and source certificates. Two different GammaMed Plus units (Varian Medical Systems, Palo Alto, USA) and two Flexitron HDR units (Elekta Ltd, Stockholm, Sweden) were used, with various local well chambers and two different types of needle, as listed in table 2.

For measurements on each afterloader, the maximum response position was used to measure charge and current for dwell times of 50, 30 and 10 s for a 16 cm source-to-chamber distance. Transit dose was determined by extrapolation from the three dwell times and was subtracted from the measured values when determining RAKR. Measurements for temperature, pressure, recombination and polarity were also taken during the time of measurement. Electrometer readings were repeated for each length of time to ensure a reproducible and stable response.

Having completed the in-house evaluation of jig scatter effects described in the previous section, scatter corrections were calculated for all data sets using Chang et al's empirical scatter estimate [15,16], using dimensions for each treatment room.

Following IAEA guidelines [2], all required correction factors were applied to calculate RAKR (K_R) from each set of measurements on each afterloader system, as shown in equation 1.

$$K_R = N_K(\frac{M_u - M_{\text{transit}}}{t})k_{\text{air}}k_{\text{scatt}}k_{\text{elec}}K_n(d/d_{\text{ref}})^2 \qquad (1)$$

where N_K is the chamber calibration factor, derived from chamber calibration certificates provided by ARPANSA, M_u is the mean temperature and pressure corrected integrated charge measurement, M_{transit} is the transit dose correction, k_{air} is the air attenuation factor, k_{scatt} is the empirically derived scatter correction; K_n is the nonuniformity (gradient) correction and $(d/d_{\text{ref}})^2$ is the inverse-square law correction (correcting for use of measurement distance d that differs from 1 m, d_{ref}).

Each calculated RAKR was compared against the corresponding decay-corrected source calibration certificate, by applying a decay correction defined as

$$K_{R,\mathrm{corr}} = K_R \; e^{\frac{0.693\times T}{T_{1/2}}} \tag{2}$$

where T is the time since calibration certificate date and time and $T_{1/2}$ is the half-life of Ir-192, 73.83 days.

RAKR measurements with well chambers

To assist in verifying the accuracy of RAKR measurements performed using the 3D printed jig, all source strength measurements were repeated using well chambers. Well chambers used for verification are listed in Table 2. All well chamber measurements were taken within an hour of the jig measurements with the exception of the Flexitron FT00668, which had to be taken in the week preceeding jig measurements due to time constraints. The dwell time used for the well chamber measurements varied depending on local protocols, which included repeated 60 s measurement, and 50 and 10 s measurements (with a subtraction to account for transit dose). The dwell position for these measurements were all taken at the position of maximum response for the well chamber.

In general, source strength is calculated with the well chamber using equation 3, with additional corrections for the Ir-192 source and applicator if applicable.

$$K_{R,\mathrm{well}} = N_{\mathrm{RAKR}} N_{\mathrm{elec}} k_{\mathrm{TP}} (\frac{M_u - M_{\mathrm{transit}}}{t}) \tag{3}$$

Here, N_{RAKR} and N_{elec} are the correction factors for the well chamber and electrometer, taken from their respective calibration certificates, k_{TP} is a temperature and pressure correction factor, and M_u and M_{transit} are the mean raw integrated charge measurement and the transit dose correction, respectively.

These measurements were also compared against the corresponding source calibration certificates, with appropriate decay corrections (see equation 2).

Results

3D printed jig fabrication, in-house testing and uncertainty budget

The jig was printed successfully using the settings listed in table 1, resulting in sturdy support system for an appropriately positioned source and chamber, with features as illustrated in figure 2.

Caliper measurements of all 2 cm pieces of the jig, which are interchangeable for different catheters and chambers, were exactly 2 cm as designed. The maximum deviation in the longer distances in the print (for example, 16 cm source to chamber distance and total length of the jig) was $\leq$ 2 mm. This deviation is most likely due to the increased warping contribution due to the

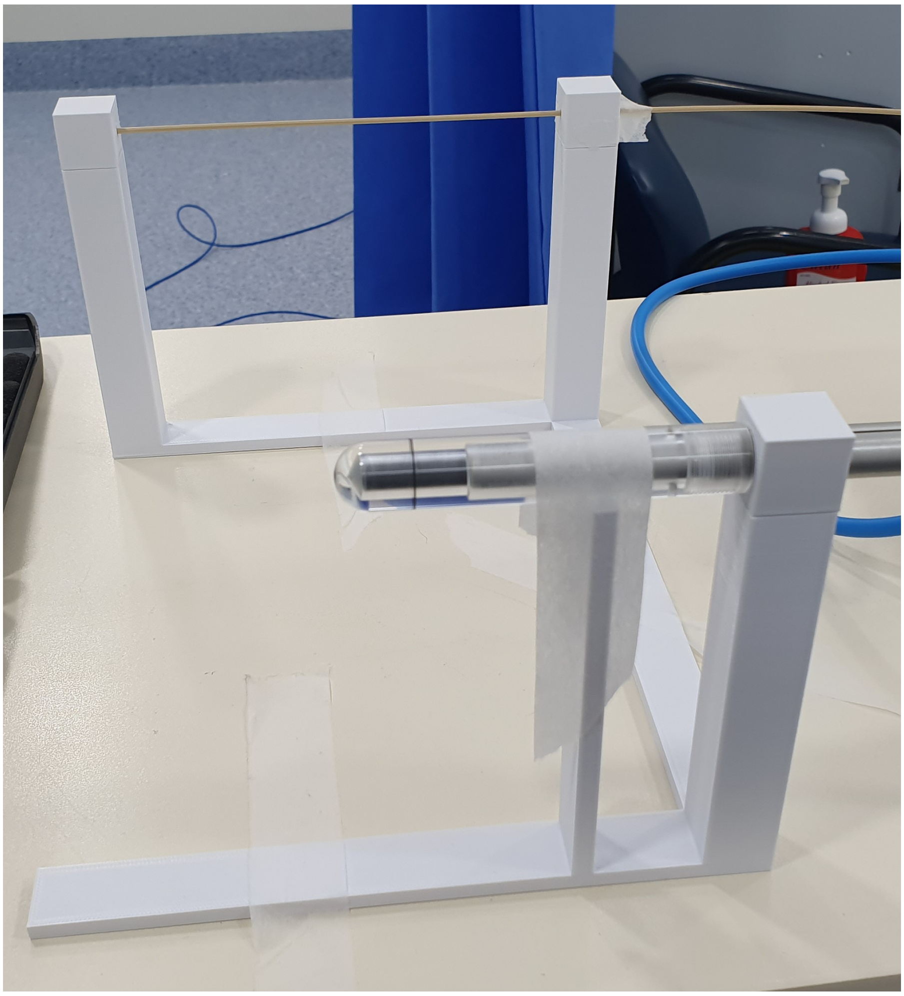

Fig. 2 Printed jig with 16cm position showing features to optimise reproducibility with PTW 30013 Farmer Chamber. This includes catheter pushed to end of holder to ensure reproducible position in longitudinal direction, chamber taped to holder to ensure stability throughout measurements and build up cap pushed against the chamber holder to ensure reproducible positioning.

large dimensions of the print, in comparison to the smaller 2 cm pieces. This deviation was included in the uncertainty budget.

The addition of a 0.5 mm tolerance to the diameter of each of the cavities in the print resulted in a fit that was secure for each object but not so tight that the equipment would be damaged. When the cube pieces that housed the cavity for the catheters to go into were plugged into the base of the jig, they were generally found to be easily interchangeable and reproducible in position. Pushing each catheter to the end of the cavity in the support and then securing it in place with a small rubber stopper ensured that catheter position remained stable and reproducible, so that certainty of consistent source positioning could be assured once the position of maximal response was determined.

As multiple pieces of the jig were fabricated, to allow for use of different chambers and catheters, slight variations in the printed geometry occasionally led to sub-optimal connections between tightly fitting components, printed despite using recommended tolerances from printer commissioning. To reduce waste, these pieces were kept and modified (either by adding adhesive tape or filing surfaces) to achieve best fit for all parts.

The comparison of values of k_{scatt} with and without the jig scatter component (i.e. in addition to room scatter) allowed the effect of the scatter due to the jig to the RAKR measurement to be evaluated, as part of the initial in-house jig testing process. The value of k_{scatt} value determined using the empirical method, based on room dimensions without contributions from the jig or other objects in the room, was 0.994. The values of k_{scatt} determined using seven distance and two distance measurements, which incorporated contributions from all scatter sources including the jig, were 0.987 and 0.992, respectively. Comparison against the empirical result shows an increase in scatter (decrease in the value of the k_{scatt} correction) of 0.7% and 0.2% when the jig and other scatter sources are included by using the seven distance and two distance methods, respectively. The potential for the jig and other scatter sources to increase the contribution of scatter to each measured RAKR beyond the degree corrected by the empirical k_{scatt}, especially when measuring in external brachytherapy centres, was therefore incorporated into the uncertainty budget for the jig by assuming a k_{scatt} uncertainty of 1.5%.

Table 3 shows the full uncertainty budget for the jig for the measurements on the GammaMed plus afterloader. The full uncertainty budget for the use of the 3D printed jig for RAKR measurements came to a total uncertainty of 3.3% k=2.

As expected the uncertainty for the well chamber measurements was less than the jig with 1.6% k = 2 uncertainty. Overall, the combined uncertainty affecting comparisons between RAKR measurements made with a Farmer chamber in the 3D printed jig and RAKR measurements made using a well chamber was calculated at 3.7 %.

Assessment of 3D printed jig reliability

Results in table 4 provide an indication of the reliability of the 3D printed jig as a tool for measuring RAKR with a calibrated Farmer chamber, by comparing results obtained with the jig to results obtained using well chambers, for the four afterloaders at three centres that were used in this multi-centre assessment.

Comparison of well chamber and Farmer chamber measurement results in table 4 shows that the differences between each RAKR measured using the jig and the corresponding RAKR measured using the well chamber were 2.9% (for GammaMed Plus PDR), -2.2% (for GammaMed Plus HDR), -3.6%

Table 3 Full Uncertainty Budget for 3D printed in-air iig

Factor	Uncertainty Contribution	Units	Ref	Type	Uncertainty
$N_{KIr-192}$	Uncertainty in derivation	Gy/C	[25]	B	4×10^{-1}
M_u	Repeatibility	pC		A	3×10^{-1}
	Calibration Cert		Cert from PTW	B	1.5×10^{-1}
	Recombination			A	1×10^{-3}
	Polarity			A	1×10^{-3}
t	Afterloader uncertainty	s	Varian document	B	2×10^{-1}
T	Resolution	C	[26]	B	2.6×10^{-4}
	Air cavity - thermometer difference		In-house measurements	A	1.5×10^{-4}
P	Resolution	hPa	[29,30]	B	2.6×10^{-6}
	Difference to true BOM pressure		In-house measurements	A	3.7×10^{-4}
$k_{humidity}$			[31]		-
k_{air}	Attenuation correction		[32]	B	2×10^{-1}
k_{scatt}	Room scatter		[16]	B	1.500
k_n	Corr. for estimate		[28]	B	1×10^{-1}
		w	[28,33]	B	5×10^{-1}
d	Error in design	mm	Wiggle room	A	2.5×10^{-1}
	Specification in chamber dimensions		[34]	B	2.5×10^{-15}
	Error from 3D print intrinsic limit		In-house and [35]	B	2×10^{-2}
$RAKR_{cert}$		mGy/h	Standard Uncertainty	5 %	
Combined Error		mGy/h	k = 2	3.3 %	

(for Flexitron S/N FT00594) and -2.9% (for Flexitron S/N FT00668). These differences are all within the 3.7% combined uncertainty of the well chamber and jig-based measurements.

Data in table 4 also indicate that all source strength measurements obtained with the 3D printed jig were within 3% of the corresponding source calibration certificate values and well within the 5% quoted uncertainty on each of the source calibration certificates.

Table 4 RAKR ((mGy/h) at 1 m) measurements from different afterloaders with uncertainty shown. Here, "% diff cert" is the calculated percentage error from the certificate value

	Certificate	Well Chamber (% diff cert)	Farmer Chamber (% diff cert)
GammaMed Plus HDR	$50.1 \pm 5\%$	$49.6 \pm 1.7\%$ (-0.9 %)	$51.0 \pm 3\%$ (2.0 %)
GammaMed Plus PDR	$4.5 \pm 5\%$	$4.6 \pm 2\%$(1.5%)	$4.5 \pm 3\%$ (-0.7 %)
Flexitron (FT00594)	$52.4 \pm 5\%$	$52.9 \pm 2\%$ (1.1 %)	$51.0 \pm 3\%$ (-2.5 %)
Flexitron (FT00668)	$52.8 \pm 5\%$	$54.1 \pm 2\%$ (2.5 %)	$52.6 \pm 3\%$ (-0.4 %)

Discussion

The 3D printed jig proved to be reproducible, easy to set up and inexpensive. The jig was successful in providing an independent measurement of the RAKR for multiple sources with different strengths and various catheters. All

Farmer chamber measurements of RAKR made using the 3D printed jig agreed with the source strength certificate value within 3% and agreed with the corresponding well chamber measurements of the same sources within the 3.7% combined measurement uncertainty.

Compared to previous studies measuring source strength with a Farmer chamber and a commercial or alternative jig, the results using this 3D printed jig are generally in agreement. Bondel et al [4] calculated that the mean percentage deviation for in-air measurements with a locally developed jig and using the seven distance scatter method was -0.94 ± 0.42. Fourie and Crabtree [10] developed a technique for calibrating source in-air that results in general agreement well within 1.5% from the certificate value, using various chambers and a scatter correction previously established by Butler et al [9]. In this study, the absolute mean percentage deviation for the jig measurements on all four afterloaders was 1.4%. This is comparable to Bassi et al's study with a 3D fabricated jig, with reported a 1.3% mean difference between measured RAKR and vendor specified value.

Uncertainty components were compared with previous estimations for in-air measurements [21,9,10,18]. The uncertainty for $N_{K,\mathrm{Ir-192}}$ was 0.4%, consistent with Butler et al and Fourie and Crabtree's previous work. Conversely, Butler et al's k_{air} estimate for the uncertainty component was lower by 0.1% and k_n higher by 0.3% than presented here. The type A uncertainties presented in this work are not consistent with van Dijk et al [21]; however, this could be due to the methodology for measuring type A components. Despite this variation, the total uncertainty in van Dijk et al's study is somewhat comparable albeit smaller at 1.0 % (k=1) compared to jig uncertainty of 3.3 % (k=2). This total uncertainty of 3.3 % (k=2) for the in-air jig in this study is slightly larger than the uncertainty calculations by Smith et al of 2.7% (k=2), which implemented a seven distance method estimation of scatter in the in-air calculation. The total RAKR uncertainty is also larger than Bassi et al's total uncertainty of 1.5% (k=2). The uncertainty for the well chamber was estimated to be 1.6 % which lies between previous well chamber uncertainty budget results of 1.3 % [36] and 3.2 % [37].

Overall, the RAKR measurements with the 3D printed jig [38] consistently provided a secondary check against well chamber measurements for all sources. Locally, the jig provides a second source calibration method independent from the standard well chamber calibration. Not only is the jig user friendly and easy to produce, it provides useful confirmation of the brachytherapy source calibration certificate which is necessary for treatment with brachytherapy sources.

The jig has been made accessible for download through Zenodo [38]. The process of calibrating a brachytherapy source in-air is not expensive or time consuming with access to a 3D printer. The following steps provide guidance for performing an independent check for brachytherapy sources with an in-air method, using the 3D printed jig evaluated in this study.

1. Ensure centre has required equipment including; cylindrical chamber calibrated for energies higher and lower than the mean source energy (e.g. 250 kV and Co-60 beam qualities), interstitial catheter (preferably 2 mm or 6 french) and a low-scatter measurement surface (wooden table, polystyrene foam block, etc).
2. If using a cylindrical chamber other than PTW 30013 or NE2571 edit the model appropriately.
3. Print the jig with settings from Table 1. Commission the jig as per methods shown in this study.
4. Following the method presented in this paper, find the position of maximum response on the catheter and use this determine correction factors for the chamber, a dwell time of 10 to 20 s will suffice. Using this same dwell position, take integrated charge measurements over 50, 30 and 10 s.
5. Take measurement of room dimensions for scatter correction and complete well chamber measurement within 1 hr of jig measurement.
6. Determine RAKR from measurements for comparison against calibration certificate value, with decay corrections.

Conclusions

The presented work shows how 3D printing can be utilised to create a low cost, easily reproducible jig for brachytherapy measurements with a cylindrical Farmer chamber with minimal effort. The jig is designed to be easily customisable depending on chambers available in brachytherapy centres and was able to determine the RAKR for an Ir-192 source from various HDR afterloaders and sources. Moreover, the jig was tested at multiple facilities to ensure robustness under varied environments. A detailed uncertainty budget was devised to provide a description of the accuracy of the measurements taken and was found to be comparable with previous studies. This supports the use of this jig as an independent source check for brachytherapy centres that do not currently have an in-air calibration solution, or those who are starting up a new brachytherapy programme. This study provides the resources and guidance to implement an in-air calibration option in a centre, including a design and method for fabricating an in-air jig that is neither time nor resource intensive, to produce reliable source strength calibration measurements.

Declarations

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Ethical approval: This article does not contain any studies with human participants performed by any of the authors.

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