

Received:
24 June 2022

Accepted:
25 September 2022

Published online:
28 November 2022

© 2023 The Authors. Published by the British Institute of Radiology under the terms of the Creative Commons Attribution-NonCommercial 4.0 Unported License <http://creativecommons.org/licenses/by-nc/4.0/>, which permits unrestricted non-commercial reuse, provided the original author and source are credited.

Cite this article as:

Bass GA, Shipley DR, Flynn SF, Thomas RAS. A prototype low-cost secondary standard calorimeter for reference dosimetry with ultra-high pulse dose rates. *Br J Radiol* (2023) 10.1259/bjr.20220638.

FULL PAPER

A prototype low-cost secondary standard calorimeter for reference dosimetry with ultra-high pulse dose rates

¹GRAHAM A BASS, ¹DAVID R SHIPLEY, BSc (Hons), ARCS, MinstP, ^{1,2}SAMUEL F FLYNN, PhD, MSci (Hons), ARCS, MinstP and ^{1,3}RUSSELL A S THOMAS, BSc (Hons), FIPEM

¹Medical Radiation Physics, National Physical Laboratory, Hampton Road, Teddington, Middlesex, United Kingdom

²School of Physics and Astronomy, University of Birmingham, Edgbaston Campus, Birmingham, United Kingdom

³Faculty of Engineering and Physical Sciences, University of Surrey, Stag Hill, Guildford, United Kingdom

Address correspondence to: Prof Russell A S Thomas
E-mail: russell.thomas@npl.co.uk

Objectives: Ultra-high pulse dose rate modalities present significant dosimetry challenges for ionisation chambers due to significant ion recombination. Conversely, calorimeters are ideally suited to measure high dose, short duration dose deliveries and this work describes a simple calorimeter as an alternative dosimeter for use in the clinic.

Methods: Calorimeters were constructed featuring a disc-shaped core and single sensing thermistor encased in a 3D-printed body shaped like a Roos ionisation chamber. The thermistor forms one arm of a DC Wheatstone bridge, connected to a standard DMM. The bridge-out-of-balance voltage was calibrated in terms of temperature. A graphite-core calorimeter was calibrated in terms of absorbed dose to water (J/kg) in Co-60 and conventional 6, 10 and 15 MV X-rays. Similarly, an aluminium-core calorimeter was calibrated in

a conventional 20 MeV electron beam and tested in a research high dose per pulse 6 MeV electron beam.

Results: Calorimeters were successfully calibrated in terms of absorbed dose to water in conventional radiotherapy beams at approximately 5 Gy/min with an estimated uncertainty of ± 2 –2.5% ($k = 2$), and performed similarly in a 6 MeV electron beam delivering approximately 180 Gy/s.

Conclusions: A simple, low-cost calorimeter traceably calibrated to existing primary standards of absorbed dose could be used as a secondary standard for dosimetry for ultra-high pulse dose rates in the clinic.

Advances in knowledge: Secondary standard calorimeters for routine measurements are not available commercially; this work presents the basis of a simple, low-cost solution for reference dosimetry for ultra-high pulse dose rate beams.

INTRODUCTION

Calorimeters are widely used in national measurement institutes around the world as primary standards of absorbed dose for conventional radiotherapy dosimetry, including the National Physical Laboratory (NPL) in the UK. The concept of calorimeters for reference dosimetry in the clinic, instead of ionisation chambers, is not new and NPL has been developing calorimeters specifically for use in clinical beams since the 1990s. A primary standard electron beam calorimeter was established at NPL in the 1990s for the calibration of secondary standard ionisation chambers (Burns et al¹), and McEwen and Duane² developed a similar portable calorimeter for use in the clinic. This was then modified for use in the ocular proton beam at Clatterbridge Cancer Centre in the UK to demonstrate how improvements in reference dosimetry for proton therapy could be achieved (Palmans et al³). Duane et al⁴ further demonstrated the feasibility of a calorimeter for clinical use

similar in size and shape to a thimble ionisation chamber and N D Lee (2015, unpublished) at NPL also developed a sophisticated prototype clinical calorimeter dimensionally identical to a Roos-type ionisation chamber, used successfully in clinical proton beams. Elsewhere, Côté and Keszti et al⁵ have developed the ‘Aerrow Mk7’, a cylindrically layered graphite calorimeter the size of a thimble ionisation chamber for dosimetry of small fields from conventional photon beams, based on the ‘Aerrow’ calorimeter by Renaud et al.⁶

It is extremely rare for a primary standard calorimeter to be used in a conventional clinical environment due to its inherently delicate nature, the requirement for it to be used in a tightly controlled environment and the length of time needed to acquire sufficient measurement data. In contrast, ionisation chambers are robust, convenient and reliable detectors as secondary standards for reference dosimetry

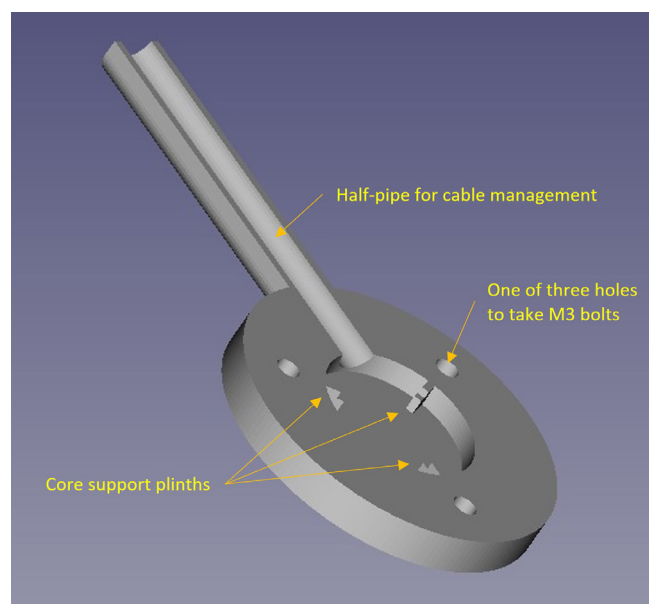
for conventional clinical radiotherapy. However, ion recombination in ionisation chambers used with ultra-high pulse dose rate (UHPDR) modalities such as FLASH and VHEE is very significant with large associated corrections and uncertainties and the use of alternative detectors, including calorimeters such as the 'Aerrow', is being explored as part of a Euromet project.⁷ The 'Aerrow' calorimeter has multiple heating and sensing thermistors for quasi-adiabatic and isothermal operation and was intended for conventional beam dosimetry in the clinic, but the measurement and control system are similar in complexity to that of a primary standard. Bourgouin et al⁸ describe a simpler calorimeter with two sensing thermistors featuring a pure aluminium core and surrounding jacket within an aluminium alloy phantom, that has been successfully tested in UHPDR electron beams. It is still somewhat removed from the familiar convenience of an ionisation chamber in a water phantom for reference dosimetry in the clinic.

In contrast, this work explores the feasibility of a simple, low-cost secondary standard level calorimeter (SSC) physically resembling a Roos-type ionisation chamber, utilising a single sensing thermistor in the core, primarily intended for clinical UHPDR modalities in existing phantoms. The characterisation of the SSC reported here is by no means comprehensive, but the initial findings were thought to be of interest to the community. Its performance was characterised for conventional radiotherapy deliveries as it would possibly need to be calibrated in conventional beams, in combination with calculated beam quality factors to enable use with other modalities. Potentially it could be calibrated directly against the NPL primary standard proton calorimeter (PSPC) using the forthcoming UK code of practice for proton beam dosimetry (to be introduced in 2023). The PSPC was successfully used in the FLASH proton beam at Cincinnati Children's Hospital prior to their commencement of the world's first human clinical trial with this modality (Mascia et al.,⁹ Lourenco et al,¹⁰ in review) and Lee et al.¹¹ A graphite-core SSC was successfully calibrated in terms of absorbed dose to water using Co-60 γ -rays and conventional 6, 10 and 15 MV x-rays (TPR_{20,10} 0.583, 0.682, 0.733 and 0.758 respectively), with an estimated expanded uncertainty of $\pm 2\%$. Uncertainties quoted in this report were evaluated in accordance with the JCGM guide to the expression of uncertainty in measurement.¹² All quoted uncertainties have been calculated from a combined standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%.) An aluminium-core SSC was calibrated in a conventional 6 MeV electron beam and a research UHPDR 6 MeV electron beam with an estimated expanded uncertainty of $\pm 2.5\%$.

Calorimeter design

The SSC physically resembles a Roos-type ionisation chamber, so potentially clinics already using this type of chamber and associated phantoms would conveniently be able to use the proposed calorimeter in the same set ups. It has a disc-shaped core 16 mm in diameter: this is the same as the sensitive air volume of a Roos-type ionisation chamber to simplify potential in-beam comparisons between the SSC and Roos chambers. The SSC has only one thermistor: the core has two 1-mm-diameter holes 1-mm deep

Figure 1. Secondary Standard Calorimeter (SSC) body showing the internal support plinths for the core



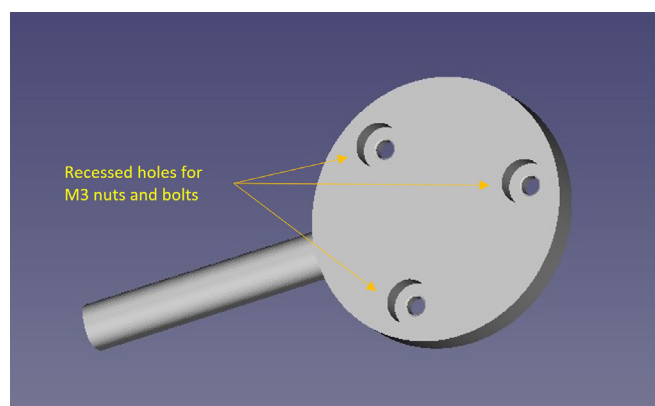
drilled into the side, one for a bead thermistor and one for an earth connection (required for signal noise reduction). The core is 2 mm deep, primarily for the practical convenience of drilling the 1 mm diameter holes in the side, coincidentally matching the Roos air volume depth. The temperature of the core is not controlled and the calorimeter can only be operated in adiabatic mode.

The body of the SSC has similar external dimensions to a Roos-type ionisation chamber, namely a 44 mm diameter and 10-mm deep disc. The SSC body was 3D-printed at NPL from polylactic acid ($C_3H_4O_2$), in two identical halves for simplicity. Figure 1 is an image taken from the CAD software showing the internal structure. The core is supported on three 1-mm-square plinths spaced 120° apart, with an air gap of 2 mm surrounding the core elsewhere. The thickness of the SSC body external face is 2 mm in the central region where the core sits and 5-mm deep around the edge (10 mm total when the two halves are brought together). A half-pipe on one side of the body and extending away from the body enables cable management. Cores were made from graphite and aluminium from readily-available materials, namely HK-75 ultra-fine grade graphite (Tokai Carbon Europe) and 1050 grade aluminium (minimum purity 99.5%). The reference point of the SSC was taken to be the geometric centre of the core. For this prototype SSC, three holes and recesses in the body are intended for M3 nylon nuts and bolts to hold the two halves of the body together, shown in Figure 2. Heatsink compound is placed in the core drill hole to improve thermal contact for the thermistor. Figure 3 is a photograph of the SSC body and core before assembly.

Sensing thermistor and bridge

The sensing thermistor used was a nominal 10 k Ω at 25°C (EPCOS thermistor, 10 k Ω resistance, NTC type, 0.8 $\times$ 1.4 mm), forming one arm of a DC Wheatstone bridge with three 10 k Ω

Figure 2. Outside face of the SSC body



high-precision resistors (Vishay 10 k Ω metal foil resistors, 10 k $\Omega \pm 0.01\%$, ± 2 ppm/ $^{\circ}\text{C}$). The supply voltage for the bridge was from a 10 V reference voltage integrated circuit (Texas Instruments REF102CP fixed series voltage reference, 10 V $\pm 0.025\%$), supplied in turn by a standard 15 V DC mains transformer. Figure 4 shows the sensing circuit, where R1, R2, and R3 are the three 10 k Ω high-precision resistors forming the Wheatstone bridge with the thermistor, supplied by the 10 V reference voltage. The bridge thermistors and reference voltage integrated circuit were housed inside an aluminium box, with the box connected to the same mains earth as the readout DMM, to minimise electrical noise.

The inherent noise and stability over time of the 10 V reference supply voltage and bridge was examined by replacing the thermistor with a fourth 10 k Ω high-precision resistor, and measuring the bridge-out-of-balance voltage over the time of a typical calorimeter measurement (a few minutes). The noise was observed to be less than ± 1 μV with no discernible drift in the bridge-out-of-balance voltage.

Figure 3. Graphite core with the two halves of the SSC body

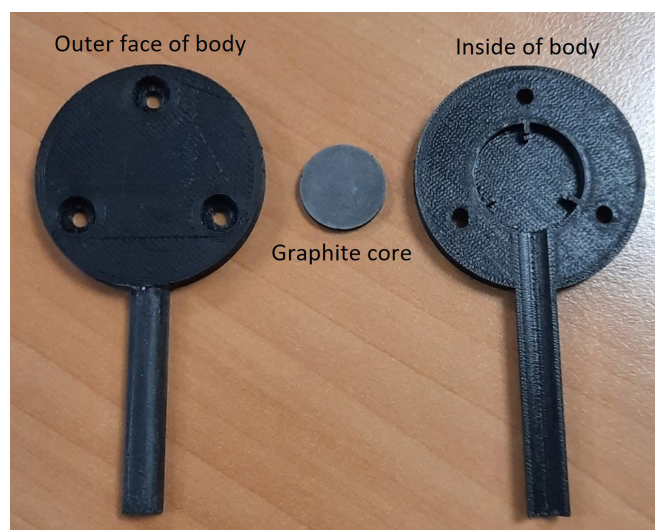
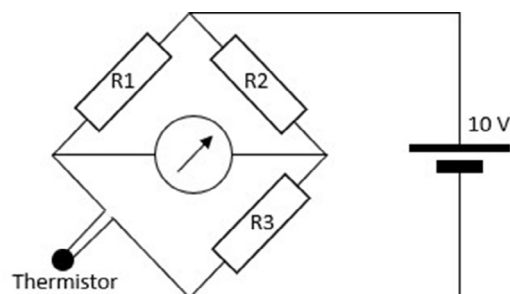


Figure 4. Sensing circuit



Readout

The out-of-balance bridge voltage from the Wheatstone bridge was connected to a 6 $\frac{1}{2}$ digit Keithley 6500 DMM in 1 V DC mode.

Calibration of the sensing thermistor and bridge

The sensing thermistor was placed in a controlled-temperature bath with a standard thermometer. The bridge-out-of-balance voltage was compared to the measured temperature at several temperatures in the range 20–25 $^{\circ}\text{C}$. The results are shown in Figure 5 including a second-order polynomial fit to the data (although a linear fit would be equally appropriate in this case). The sensitivity of the bridge in terms of out-of-balance volts per $^{\circ}\text{C}$ (or K) is approximately 0.1 V per K, so the bridge noise of ± 1 μV reported above equates to ± 10 μK . To give this context, a dose of 1 Gy to the core results in a temperature rise of approximately 1500 μK (1.5 mK).

Software and analysis

Software was written in-house to acquire and analyse the data, using LabVIEW and Microsoft Excel respectively. Figure 6 shows a typical measurement with the graphite core SSC with samples every 0.2 s. This software-requested sampling rate was sufficiently frequent to accurately track the changes in core temperature but not too frequent to be affected by Windows task-sharing and the DMM itself performing some averaging of readings in order to reduce noise. The exposure room at NPL where these measurements were performed is closely maintained at approximately 20 $^{\circ}\text{C}$, and the positioning of the SSC at

Figure 5. Calibration of bridge with thermistor

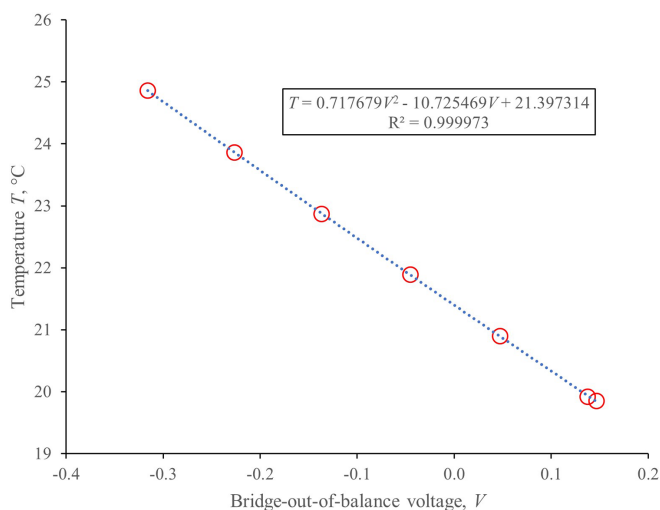
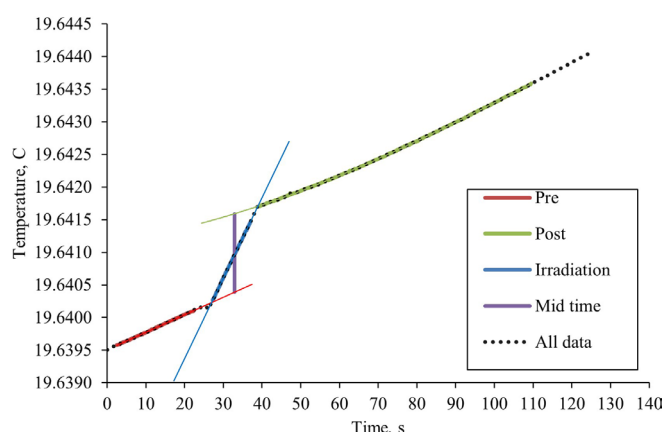


Figure 6. Typical graphite-core SSC measurement and analysis, 6MV x-rays, 100 MU delivered (1 Gy).



several centimetres deep within a relatively large phantom in normal use insulates it somewhat from ambient temperature changes. Once set up in the phantom the SSC is left to equilibrate with the ambient room temperature prior to starting measurements but this is likely to still result in a rising or falling underlying temperature drift. Figure 6 shows the SSC temperature drifting up over the time of the readings for this particular measurement. It can also be seen that when the irradiation starts the measured temperature is offset negatively by approximately 0.1 mK, an electrical effect due to the operation of the linac observed occasionally with other calorimeters; the offset disappears at the end of the irradiation. A similar effect was noted by Renaud et al.¹³

The temperature gradient of the core before and after the exposure is sufficiently similar to indicate the thermal isolation of the core is reasonable, although a slight curve in the post-exposure temperature drift demonstrates (expected) heat loss from the core. Analysis of the pre- and post-exposure data for the SSC was therefore performed using the mid-run extrapolation technique, *i.e.* a linear fit to the data before the irradiation and a second-order polynomial fit to the data after the irradiation was performed, both extrapolated to the mid-point of the irradiation in order to calculate the temperature rise due to the dose delivered that allows for the background temperature drift. A second-order polynomial fit to the post-exposure data sufficiently modelled the non-linear temperature drift of the core but also predicted reasonable temperatures when extrapolated back to the mid-point of the exposure; higher order polynomial fits to the post-exposure data resulted in greater variation in mid-point temperature and sometimes implausible curve shapes outside of the data range. In contrast, Côté et al.⁵ record substantial heat loss for the Aerrow Mk7 (the only similar instrument to compare the SSC with) both during and after an exposure of approximately 15 s so that the mid-run extrapolation technique was not suitable.

Results of measurements with graphite-core SSC in photon beams

Although the SSC is intended for UHPDR environments, the performance of a graphite-core SSC was examined in conventional linac MV x-rays by cross-comparison with a calibrated NPL2611 secondary standard photon ionisation chamber, in a solid water phantom (St Bartholomew's Hospital WTe, for

convenience). Measurements were performed at 6, 10 and 15 MV nominal energies ($\text{TPR}_{20,10}$ 0.682, 0.733 and 0.758, respectively). The linac output was approximately 1 cGy/MU at 400–500 MU/min (4–5 Gy/min) at the reference point. The reference point of the SSC was taken to be at the centre of the core. 100 MU (approximately 1 Gy) exposures were delivered to the calorimeter, ten times at each beam quality. The process was repeated on consecutive days. The typical standard deviation of the mean (sdom) of 10 SSC measurements was 0.3% (compared to 0.03% or less using five measurements with the NPL2611 and electrometer). The mean difference of the second day's calibration factor result compared to the first day's result was 0.4%; for comparison, NPL2611 ionisation chambers calibrated in MV x-rays at NPL over consecutive days would typically repeat within 0.2%. The mean values of actual dose for 100 MU delivered, SSC temperature rise ΔT in Kelvin and calculated calibration factor Gy/K are presented in Table 1. The overall expanded uncertainty of the SSC calibration factor (when calibrated against a secondary standard ionisation chamber) for 1 Gy delivered is estimated to be $\pm 2\%$.

A similar set up was used to perform a calibration of the graphite-core SSC with Co-60 γ -rays. The SSD of the phantom was reduced from the reference distance of 95 to 60 cm (the practical minimum) to maximise the dose rate at the SSC (to approximately 1.4 Gy/min). The collimator setting of the Co-60 irradiator was adjusted to give a 10×10 cm field size at 5 cm deep in the phantom. The source was exposed for 60 s for measurements with the secondary standard chamber and SSC, resulting in a greater dose (and hence temperature rise) to the core but over a considerably longer time in comparison to that during the MV X-ray 100 MU exposures described above (15–20 s exposures). The mid-run extrapolation analysis was therefore expected to result in greater uncertainty in the calculated dose. The sdom of 12 SSC 60 s readings was 0.5% compared to 0.3% for 10 SSC readings for 100 MU.

Linearity of graphite-core SSC response with dose delivered (MV x-rays)

The calibration of the graphite-core SSC was performed with deliveries of approximately 1 Gy (100 MU), resulting in a measured core temperature rise of only 1.2 mK. A larger dose will result in a correspondingly greater temperature rise in the core and correspondingly lower measurement uncertainties (the primary standard calorimeters at NPL are routinely given 2 Gy per measurement), but the increased time of the delivery means that external temperature drifts and heat transfer may have a more significant effect on the uncertainty of the analysis of the core temperature measurement. To investigate this, measurements were performed with deliveries of 50, 100, 150, 200, 250 and 500 MU at one beam energy, 6 MV, at 5 Gy/min dose rate. Ten measurements were performed for 100 and 200 MU delivered, and five measurements at each of the other MU settings. Figure 7 shows the SSC response in terms of temperature rise in Kelvin per MU, relative to the value for 100 MU delivered (as per the calibration measurements).

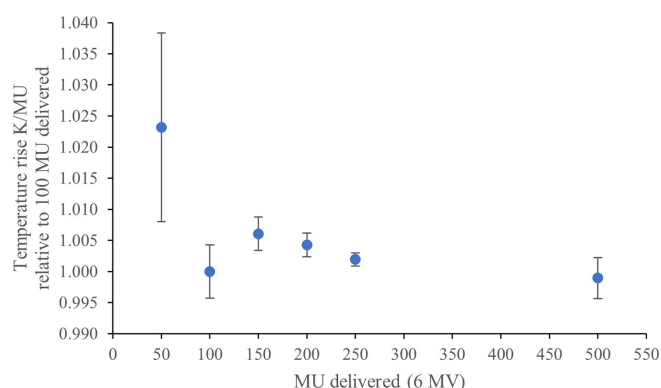
The results indicate that the temperature rise for 50 MU delivered (0.5 Gy) is too low to be measured with adequate accuracy

Table 1. Calibration of graphite-core SSC in photon beams

Nominal Energy (TPR _{20,10})	Depth cm	Field size cm×cm	SSD cm	Dose rate Gy/min	Actual dose cGy	SSC ΔT K	Calibration coefficient ^a	
							Gy/K	Relative to Co-60
Co-60 (0.568)	5	10 × 10	60	1.4	141.0	0.0016728	842.6	1.000
6MV (0.682)			95	5.0	99.39	0.0011916	836.0	0.992
10MV (0.733)					99.46	0.0011905	837.1	0.993
15MV (0.758)	7		93	4.5	95.42	0.0011347	842.4	1.000

^aCorrected to 20°C, allowing for the temperature-dependency of the specific heat capacity of graphite. A correction for the beam non-uniformity over the area of the SSC core relative to the NPL2611 chamber volume was estimated from beam profile data and found to be less than 0.1% for all energies and is not included here.

Figure 7. Graphite-core SSC temperature rise per MU delivered relative to 100 MU deliveries (6 MV). The error bars indicate the sdom of the repeated measurements for each MU set.



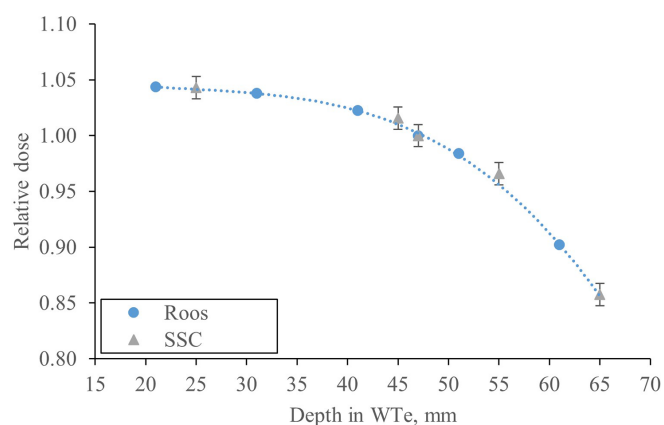
by this system. The data set is small, but the repeatability of the readings appears to improve significantly with dose delivered up to 250 MU (2.5 Gy). 200–250 MU delivered (2–2.5 Gy delivered in approximately 30 s) appears to be optimal for this SSC in this set up.

PDD measurements with aluminium-core SSC in conventional linac electron beam

A calibrated Roos ionisation chamber in a WTe solid water phantom was used to perform measurements of 3×100 MU delivered at seven depths around the reference depth z_{ref} (4.7 cm) for a conventional linac 20 MeV electron beam. An aluminium-core SSC was then used in the same phantom to measure the temperature rise in the core (and hence relative dose) for 20 MeV, 5×200 MU deliveries at five different depths around the reference depth. The Roos ionisation measurements were converted to dose using published data. The Roos-derived depth-dose relative to z_{ref} compared to the SSC-derived depth-dose measurements are presented in Figure 8.

The sdom of three measurements at each point with the Roos chamber was typically less than 0.1% and the sdom of five measurements with the SSC was typically 0.7%. The shape of the relative depth-dose curves is similar for the different detectors.

Figure 8. Relative depth-dose measurement comparison between Roos and aluminium-core SSC



The calibration coefficient in terms of Gy/K of this SSC could also be obtained from the measurements at z_{ref} depth, and was calculated to be 1065 Gy/K at 20°C with an estimated expanded uncertainty of $\pm 2\%$.

Results of high dose rate measurements with aluminium-core SSC in a research 6 MeV electron beam

A separate NPL project to investigate different detector responses to UHPDR-type deliveries was in progress at the same time the SSC was being investigated, so it was decided to include the SSC in beam measurements.

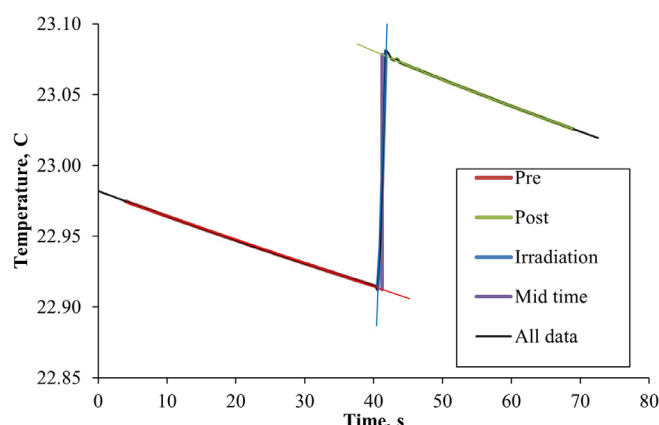
The NPL conventional Elekta linac 6 MV x-ray beam was modified to deliver a UHPDR-type 6 MeV electron beam, basically by removing the target from the 6 MV beam. The internal beam monitor chamber is also removed in this mode so the delivered beam does not have the same level of control compared to the normal state. A basic beam monitor was provided by a diode placed in the beam and connected to a pulse counter circuit providing a beam termination signal to the linac after a pre-programmed number of delivered beam pulses. It was decided to fix the number of beam pulses to 400 for all measurements in this mode.

To measure the output the UK primary standard graphite calorimeter for electron beams was set up at 70 cm SSD and used to measure the dose from 400 pulses delivered (in approximately 1 s) by the linac in the UHPDR mode. The effective point of measurement was equivalent to 13-mm depth in water, the depth of dose maximum derived from a PDD measurement using film. The mean calculated dose to water of 25 such deliveries was 180.9 Gy at the reference depth. (Several corrections are applied to the primary standard calorimeter response in 6 MeV reference conditions to obtain dose; it was assumed for the purposes of this experiment that the same corrections were applicable in these non-reference conditions.) The sdom of the mean dose obtained with the primary standard was 0.4%; this is similar to the sdom of 20 readings of conventional 2 Gy, 6 Gy/min 6 MeV deliveries typically obtained with the primary standard calorimeter under reference conditions.

The aluminium-core SSC was set up in a WTe phantom at 70 cm SSD with the reference point of the core at 13 mm water equivalent depth, and 25 exposures of 400 pulses delivered. The temperature rise from 400 beam pulses delivered in 1 s was approximately 0.16 K. Figure 9 shows a typical response of the SSC to a UHPDR delivery, including a settling feature immediately after beam off noted in some of these measurements.

Combining the dose output measurement from the primary standard calorimeter with the mean temperature rise of the SSC resulted in a calibration coefficient for the SSC of 1139 Gy/K at 20°C (sdom 0.5 %) with an estimated expanded uncertainty of $\pm 2.5\%$. The calibration coefficient at this 6 MeV UHPDR quality is therefore approximately 7% higher to that obtained at the conventional 20 MeV beam quality, but this comparison only relates to the beam quality and not dose rate. The dose within the

Figure 9. Typical response of the aluminium-core SSC to research UHPDR delivery of approximately 180 Gy in 1 sec



2-mm-thick core for 6 MeV also reduces significantly with depth along the beam axis compared to 20 MeV. It might be informative to calibrate the SSC over the full range of conventional electron beam qualities using the same dose rate throughout.

DISCUSSION AND CONCLUSION

Simple, low-cost secondary standard calorimeters ultimately intended for UHPDR dosimetry have been constructed and successfully tested in Co-60 γ -rays, conventional MV x-ray and electron beams and a research UHPDR electron beam. The standard deviation of the mean of ten measurements of 1 Gy dose for conventional modalities using the SSC is typically 0.3 %, *i.e.* an order of magnitude larger than a secondary standard ionisation chamber and electrometer. The convenience of use of an ionisation chamber for routine measurements in conventional radiotherapy beams is not challenged by the SSC in its present form; in particular, a single calorimetry measurement takes significantly longer due to the acquisition of pre- and post-exposure drift data. However, despite the uncomplicated design of the SSC and the simplicity of the sensing circuitry, the results for conventional 1–2 Gy dose measurements show the SSC to be a practical dosimeter even for lower dose levels than ultimately intended for this device. The SSC measurements in the UHPDR electron beams have a much greater signal to noise ratio than for conventional dose deliveries, and since the higher dose is also delivered over a much shorter time one might expect the sdom of these measurements to be lower than for the conventional dose deliveries: the similar sdom from the UHPDR data reported here could simply be due to the greater variation in the output from the linac in this experimental mode rather than the SSC performance. Independent verification of the stability or otherwise of the linac output is required to isolate the SSC variability.

Future work

Various areas for further development have been proposed including

- a waterproof version of the SSC and associated characterisation in water

- Monte Carlo modelling of the SSC to establish beam quality- and modality-dependent correction factors and potential use of the SSC as an absolute dosimeter
- calibration of the SSC over the full range of conventional linac electron beam energies, repeat calibrations at Co-60 and MV x-rays to verify behaviour
- further linearity tests to verify useful dose and dose rate range
- further testing of the SSC and comparison with other detectors in UHPDR beams
- an SSC version shaped like the IBA PPC05 ionisation chamber (commonly used in clinical proton beams)
- comparison of the SSC with the NPL primary standard proton calorimeter in clinical proton beams
- optimisation and automation of analysis.

REFERENCES

1. Burns DT, McEwen MR, Williams AJ. An NPL absorbed dose calibration service for electron beam radiotherapy. In: *International symposium on measurement assurance in dosimetry*. Vienna, Austria 24-27 May. IAEA-SM-330/34; 1993, pp. 61–71.
2. McEwen MR, Duane S. A portable calorimeter for measuring absorbed dose in the radiotherapy clinic. *Phys Med Biol* 2000; **45**: 3675–91. <https://doi.org/10.1088/0031-9155/45/12/312>
3. Palmans H, Thomas R, Simon M, Duane S, Kacperek A, DuSautoy A, et al. A small-body portable graphite calorimeter for dosimetry in low-energy clinical proton beams. *Phys Med Biol* 2004; **49**: 3737–49. <https://doi.org/10.1088/0031-9155/49/16/019>
4. Duane S, Aldehaybes M, Bailey M, Lee ND, Thomas CG, Palmans H. An absorbed dose calorimeter for IMRT dosimetry. *Metrologia* 2012; **49**: S168–73. <https://doi.org/10.1088/0026-1394/49/5/S168>
5. Côté B, Keszti F, Bancheri J, Sarfehnia A, Seuntjens J, Renaud J. Feasibility of operating a millimeter-scale graphite calorimeter for absolute dosimetry of small-field photon beams in the clinic. *Med Phys* 2021; **48**: 7476–92. <https://doi.org/10.1002/mp.15244>
6. Renaud J, Marchington D, Seuntjens J, Sarfehnia A. Development of a graphite probe calorimeter for absolute clinical dosimetry. *Med Phys* 2013; **40**(2): 020701. <https://doi.org/10.1118/1.4773870>
7. Schüller A, Heinrich S, Fouillade C, Subiel A, De Marzi L, Romano F, et al. The european joint research project uhdpulse-metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates. *Phys Med* 2020; **80**: 134–50. <https://doi.org/10.1016/j.ejmp.2020.09.020>
8. Bourgouin A, Schüller A, Hackel T, Kranzer R, Poppinga D, Kapsch R-P, et al. Calorimeter for real-time dosimetry of pulsed ultra-high dose rate electron beams. *Front Phys* 2020; **8**. <https://doi.org/10.3389/fphy.2020.567340>
9. Mascia A, Zhang Y, Lee E, Speth J, Sertorio M, Abel E, et al. Commissioning a fixed field FLASH pencil beam scanning proton therapy system in support of the first in-human clinical trial. *AAPM* 2021. Available from: [Virtual Annual Meeting & Exhibition, 25-29 July](https://www.aapm.org/meetings/2021AM/programInfo/programAbs.php?sid=9340&aid=57614). Available from: <https://www.aapm.org/meetings/2021AM/programInfo/programAbs.php?sid=9340&aid=57614>
10. Lourenco AM, Subiel A, Lee N, Flynn S, Cotterill J, Shipley D, et al. Absolute dosimetry for FLASH proton pencil beam scanning radiotherapy. *Scientific Reports (in Review)* 2022.
11. Lee E, Lourenco AM, Speth J, Lee N, Subiel A, Romano F, et al. Ultra-high dose rate pencil beam scanning proton dosimetry using ion chambers and a calorimeter in support of first in-human FLASH clinical trial. *Med Phys* 2022 Sep; **49**(9):6171–6182. <https://doi.org/10.1002/mp.15844>. [Epub 2022 Jul 14]
12. JCGM 100:2008, Guide to the Expression of Uncertainty in Measurement (Joint Committee for Guides in Metrology, 2008). Available from: <https://www.bipm.org/en/publications/guides/#gum>
13. Renaud J, Sarfehnia A, Bancheri J, Seuntjens J. Aarow: A probe-format graphite calorimeter for absolute dosimetry of high-energy photon beams in the clinical environment. *Med Phys* 2018; **45**: 414–28. <https://doi.org/10.1002/mp.12669>