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SCIENTIFIC NOTE

A method for obtaining three-dimensional measurements of HDR brachytherapy dose distributions using Fricke gel dosimeters and optical computed tomography

Andre Asena[1] · Sanna Nilsson[2] · Shaun T. Smith[1] · Tanya Kairn[1,3] · Scott B. Crowe[1,3] · Jamie V. Trapp[1]

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Abstract
This study aimed to develop a method for performing accurate, high-resolution, three-dimensional (3D) Fricke gel dosimetry measurements of high dose rate (HDR) brachytherapy dose distributions using optical computed tomography (CT). A multi-needle brachytherapy gel phantom was purpose-built to contain four stainless-steel brachytherapy needles and a sample of Fricke Xylenol gel. A Paris-style HDR brachytherapy treatment was planned and delivered to the gel, which was then read out using a novel optical CT scanning method; all the brachytherapy needles were removed prior to scanning and replaced with a refractive index matched fluid. The removal of the stainless-steel needles during pre- and post-irradiation scanning minimised the potential for artefacts caused by missing ray-sum data. Results showed good agreement between measured and calculated doses (within 1%) at all positions greater than 0.1 cm from each needle. This study demonstrated that 3D Fricke gel phantoms may be valuable tools in verifying HDR brachytherapy treatments. The phantom construction and optical CT scanning method proposed in this work has the potential to enable routine quality assurance measurements of complex HDR brachytherapy treatment deliveries via accurate and detailed three-dimensional dose measurements.

Keywords Optical computed tomography · Fricke gel · Brachytherapy

Introduction

High-dose rate (HDR) brachytherapy uses radioactive sources that are placed within or adjacent to tumours in the body, to efficiently deliver high doses of radiation to localised volumes of tissue, while the steep dose fall-off around the brachytherapy source effectively spares surrounding organs [1]. Accurate measurement of the high dose gradients around HDR brachytherapy sources requires the use of a dosimetry system with high spatial resolution, flat energy response, and high sensitivity. Many non-chemical dosimeters that are widely used in other areas of radiation therapy are unsuitable for HDR brachytherapy dosimetry due to their large size (resulting in volume averaging, a lack of spatial resolution and perturbation of the dose distribution) and their inability to provide detailed two or three-dimensional information [2].

Radio-sensitive dosimetry gels containing suspended ferrous-sulfate Fricke solution [3] have been proposed as capable of providing accurate one-, two- or three-dimensional measurements of dose distributions produced by HDR brachytherapy sources [4–6], due to their approximate water equivalence (lack of dose perturbation), energy independence (above 30 keV), and linear dose response (between 0.1 and 30 Gy) [7–9]. Specifically, studies by Carrara et al. [4, 5] have demonstrated the potential of Fricke gels for measuring HDR brachytherapy dose, either in stacks of two-dimensional planes alongside the HDR source [4] or in narrow catheters inserted into the phantom (or potentially patient) dispersed between HDR brachytherapy needles [5].

Three-dimensional measurements of HDR brachytherapy dose distributions have previously been achieved using polymer-based (rather than Fricke-based) dosimetry gels that

✉ Tanya Kairn
t.kairn@gmail.com

1 School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane, QLD 4000, Australia

2 Nelune Comprehensive Cancer Centre, Prince of Wales Hospital, Randwick, NSW 2031, Australia

3 Cancer Care Services, Royal Brisbane & Women's Hospital, Butterfield Street, Herston, QLD 4029, Australia

were read out using magnetic resonance imaging (MRI) [2, 10, 11]. To avoid perturbing the MRI signal, these studies used plastic catheters [2, 10, 11] rather than the stainless-steel needles that are also used in the more-complex HDR brachytherapy treatments of sites such as prostate [1]. The achievable dose resolution in these studies was limited by unexplained dose differences in low-dose regions [2, 10], oxygenation of the gel in regions close to the catheter [2] and the need to compromise MRI spatial resolution [2] or use elevated prescription doses (up to 20 Gy) [11] to overcome the inherent noise in the MRI scans.

Optical computed tomography (CT) imaging has been shown to produce high-resolution, low-noise, three-dimensional dose images, when used to read out dosimetry gels in general [12, 13] and Fricke gels in particular [8, 14]. However, when opaque objects are contained in the gel, missing reconstruction ray-sum data can lead to substantial artefacts in the resulting optical CT reconstruction [15–17] which can substantially degrade the accuracy of the resulting three-dimensional dose measurement [15, 16]. The presence of the opaque catheters or needles that are used to deliver HDR brachytherapy treatment doses to dosimetry gels [2, 10, 11] has the potential to severely limit the accuracy and detail that would otherwise be achievable via optical CT read out of Fricke gels, even if the catheters are made from plastic.

This study aimed to develop a method for performing accurate, high-resolution, three-dimensional Fricke gel dosimetry measurements of HDR brachytherapy dose distributions by adapting an optical CT based gel dosimetry technique that was previously established for measuring external beam radiotherapy dose distributions around metal implants [17].

Methods

Fricke gel phantoms

The Fricke Xylenol (FX) gel dosimeters used in this study were composed of: gelatin from porcine skin of 300 Bloom strength, 50 mM sulfuric acid, 0.2 mM ferrous sulfate (FS), 0.2 mM xylenol orange (XO), and Milli-Q water [18]. The gel formulation was mixed with a magnetic stirrer while the heat was maintained at approximately 45 °C.

Two gel phantoms were created; one was designed to hold a single needle, for use in normalising the voxel values from the gel readout, and the other was designed to hold four parallel needles, to act as the measurement phantom. Both gel phantoms used cylindrical plastic containers with height 14 cm and diameter 7 cm. The gel phantoms were designed and created using a 3D printing (rapid prototyping) process [19, 20], so that the ultimate positions of the HDR treatment needles could be precisely determined, to avoid the alignment issues encountered in Senkesen et al's polymer-gel-based study of HDR brachytherapy dose [10].

Figure 1 shows the schematics of both gel phantoms including custom designed and 3D printed needle positioners and stabilisers. These were created in SketchUp Make 8 (Trimble Navigation Limited, Sunnyvale, California, USA) before being exported as stereolithography files and printed on a MakerBot Replicator 2 (MakerBot, Brooklyn, NY) using polyactic acid (PLA) filament. Each phantom used 0.2 cm stainless steel needles that were positioned before the gel was poured and allowed to set for 24 h by refrigeration at approximately 4 °C. In the measurement phantom, the four needles were arranged to form a square with a separation distance of 2 cm, while the normalisation phantom had its needle placed along the central axis of the container.

Brachytherapy treatment planning and irradiation

The two phantoms containing the FX gel were CT scanned on the day of irradiation, and HDR brachytherapy treatments were planned using the Oncentra Brachy treatment planning system (TPS) version 4.3 (Elekta AB, Stockholm, Sweden) with a model ^{192}Ir source and a dose calculation algorithm based on the report of the AAPM's task group 43 [21] (abbreviated to TG-43) which was used to calculate dose at resolution of $0.1 \times 0.1 \times 0.1$ cm^3.

To produce a dose distribution for use in normalising the FX gel, a treatment plan was created for the single-needle gel phantom. This treatment plan modelled a line source by using equally-spaced dwell positions and equal dwell times, for the ^{192}Ir source, which produced a circular dose distribution across the axial plane of the phantom. For the measurement phantom, which contained four equally-spaced parallel needles, a Paris-style treatment was planned, using equally-spaced dwell positions and equal dwell times to produce a dose distribution that varied across the axial plane of the phantom. Both treatment plans used 45 dwell positions per needle, with a uniform step size of 0.25 cm.

A prescription dose of 300 cGy was defined at a point 1 cm lateral to the needle in the normalisation phantom and 1 cm lateral (towards the container wall) from any one of the needles in the measurement phantom, in a plane at the vertical centre (7 cm from the base) of the gel. To achieve this dose, the normalisation treatment plan used dwell times of 5.3 s and the measurement treatment plan used dwell times of 2.1 s for each dwell position.

After placing each phantom in a water tank to ensure sufficient scatter conditions, the afterloader was connected to each needle and the respective treatment plan was delivered.

HDR brachytherapy irradiations were performed using a Nucletron Microselectron remote afterloader (Elekta AB, Stockholm, Sweden). The afterloader used a ^{192}Ir source with an active length of 0.36 cm and a diameter of 0.065 cm.

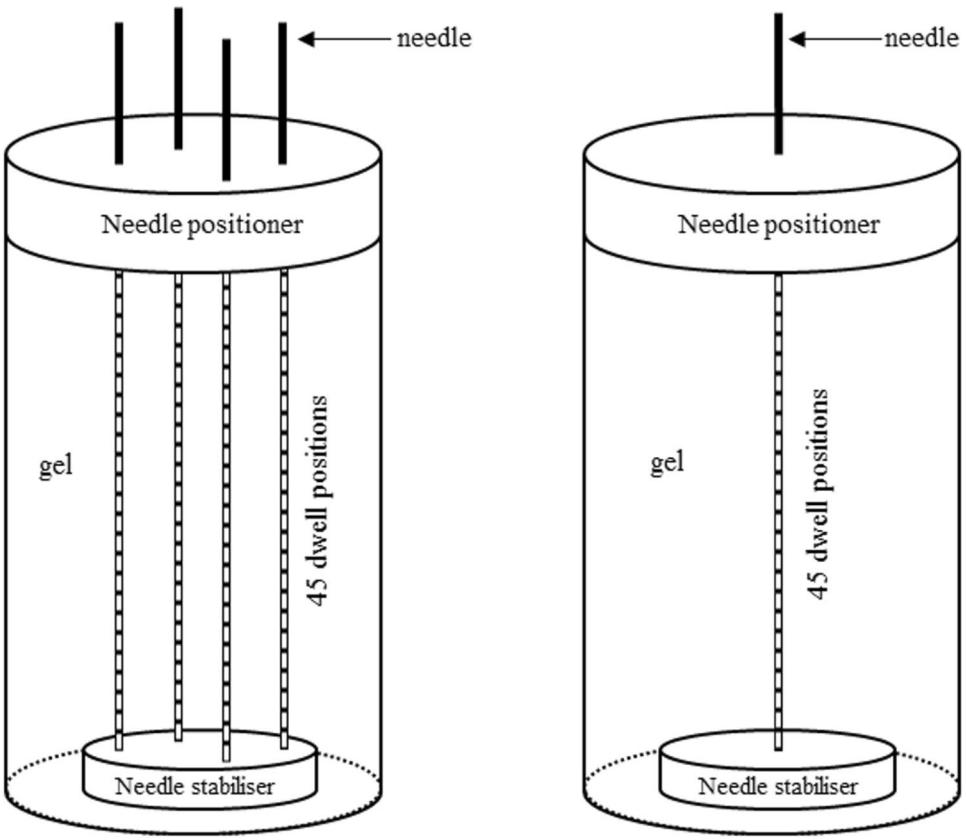

Fig. 1 Design of the measurement phantom (left), and normalisation phantom (right)

At the time of irradiation, the source strength in terms of Air Kerma was 29.92 mGy cm^2 h^{-1}.

Optical CT scanning

To obtain accurate and detailed optical CT images of the irradiated gel phantoms, it was necessary to adapt a method previously proposed to eliminate reconstruction artefacts caused by the presence of opaque medical implants in polymer gels used to measure external beam radiotherapy dose distributions [17]. Briefly, the stainless-steel brachytherapy needles were removed during pre- and post-irradiation scanning, and the cylindrical cavities that remained were filled with refractive index matched fluid made up of Glycerol [17], combined with an identical FX solution without the gelling agent (10 volume parts 0.2 mM FX solution to 3 parts Glycerol).

Using this method, each Fricke gel phantom was optically CT scanned before irradiation (to allow background subtraction [22]) and then optically CT scanned again, after irradiation, using a Vista Optical CT Scanner with VistaRecon software (Modus Medical Devices Inc., London, Canada). Between irradiation and scanning, a development time of 50 min was used, as this period equated to the 50 min development time observed for FX solutions with 0.2 mM ferrous sulfate concentrations [18] and exceeded the 30–40 min wait time that is generally recommended for FX gels to minimise measurement uncertainties due to development time and diffusion [23, 24], while also fitting conveniently into our clinical workflow.

Data analysis

In-house Matlab code (MathWorks, Natick, USA) was used to subtract the background image from each optical CT scan, to produce three-dimensional arrays of net optical density, which were converted to dose using a factor determined as the ratio of the 300 cGy prescription dose to the net optical density at the normalisation point (1 cm distance from the needle) in the normalisation phantom. This method assumes that the TPS (i.e. TG-43) provides an accurate dose calculation at the normalisation point, in this homogeneous phantom, with this simple line-source treatment geometry, and relies on the linear relationship between dose and net optical density that has been established for FX gels [6, 25].

The three-dimensional dose distribution produced by the TPS was exported in DICOM format, for the normalisation treatment plan and the measurement treatment plan. These planned dose distributions were each registered to the corresponding three-dimensional dose array from the gel measurements, by iteratively shifting the locations of all voxels in the measured dose distribution until the locations of dose

maxima were matched; no deformations were applied. In-house Matlab code was used for data registration and subsequent output and analysis of dose comparison data.

Results

In the normalisation gel, the dose at the prescription point matched the planned dose of 300 cGy by definition. Good agreement (within 1%) was achieved at all measured points further than 0.1 cm from the needle. This result confirms the linear response of the FX gel, over a dose range from 100–800 cGy.

Comparisons of planned and measured dose profiles in the measurement gel are shown in Fig. 2. There is a generally good agreement across all profiles except in the high dose regions 0.1 cm from the needles (Fig. 2a). At this location there is a discrepancy of approximately 4% when the dose exceeds 800 cGy.

Discussion

The slight deviation between the dose measured in the gel and calculated by the TPS in regions within 0.1 cm of the brachytherapy needles may be a consequence of the TG-43 model used by the TPS, which assumes that everything beyond the encapsulated ^{192}Ir is a homogeneous medium, including the thin stainless-steel walls of the brachytherapy needles. Alternatively, this small dose difference may be entirely attributable to the effects of the steep dose gradients that occur close to the source, including volume averaging or registration uncertainties.

Compared with previously published studies that have used FX gels and the Vista optical CT to evaluate dose distributions from intensity modulated [26, 27], stereotactic ablative [28] and static [23] external beam radiotherapy as well as superficial HDR brachytherapy treatments [6], the level of agreement between the planned and measured

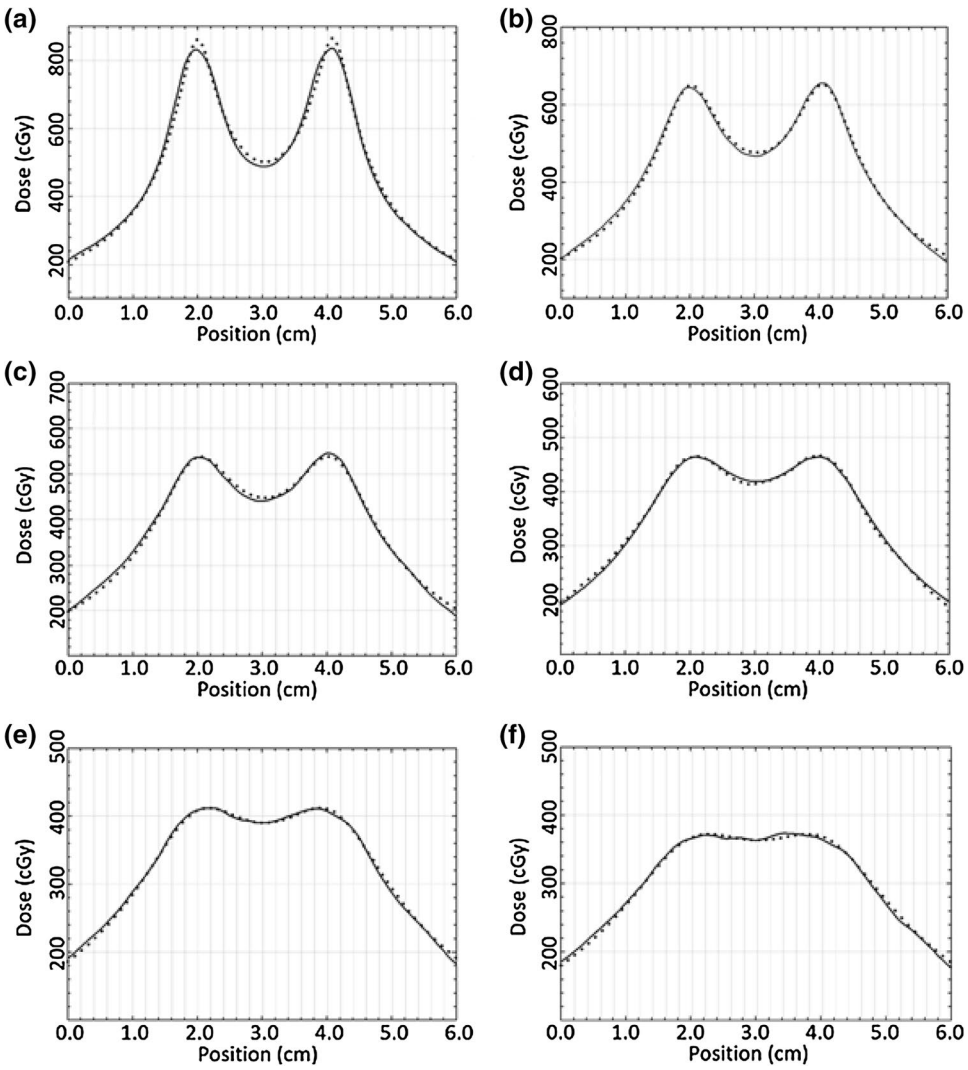

Fig. 2 Measured dose profiles (solid lines) versus dose profiles taken from TPS system (dotted lines) at profile locations moving from one pair of needles towards the other pair of needles, by distances of **a** 0.1 cm, **b** 0.2 cm, **c** 0.3 cm, **d** 0.4 cm, **e** 0.5 cm, and **f** 0.6 cm. Note that the measured dose in cGy shown here is derived from a normalisation measurement in a separate gel sample and not from the independent production of a calibration curve

doses achieved in the current study is unusually close. For example, Jordan et al. observed agreement within 3% between measurements made using FX gel and using a commercial diode array, for one intensity modulated radiotherapy (IMRT) treatment beam [26], and Babic et al. reported dose differences of 2–3% between planned and measured IMRT doses when an FX gel was placed inside a head and neck phantom [27].

The uncertainty budget provided by Pappas et al., in their investigation of HDR brachytherapy dose calculation accuracy using FX gel [6], provides an indication of how the currently study achieved such close agreement (generally within 1%) between planned and measured doses. Sources of dosimetric uncertainty reported by Pappas et al. include the calibration of the gel using a linear accelerator and the specification of the source air kerma strength, as well as the reproducibility of optical density characteristics and temperature histories between gel samples [6]. Because the current study used gel from the same batch (irradiated and read out within minutes of each other, under the same temperature conditions) for both normalisation and measurement, and normalisated the gel using a dose point from the brachytherapy TPS rather than an independent system such as a linear accelerator, the results reported herein have avoided the major uncertainties affecting previous studies. This may be either an advantage or a disadvantage, when considering clinical implementation of this method.

Reliance on the TPS for normalisation removes uncertainties due to both linear accelerator output and ^{192}Ir source strength, but has the potential to obscure gross errors such as inaccurate date and time specification (or inaccurate decay calculations) or incorrect source strength specification in the TPS. These errors would need to be investigated and eliminated using more conventional routine quality assurance and data entry checks.

This study was also limited by not including a separate characterisation of the specific gel formulation and production process used to obtain the results. Auto-oxidation effects in the gel [27] were not measured and were assumed negligible with respect to the measured dose levels.

The gel normalisation method used herein relies on the assumption that the dose calculation provided by the TPS at the normalisation point is correct. It is therefore very important to eliminate or minimise more subtle sources of dosimetric error, such as the lack of full scatter around the relatively small containers that are often used for gel dosimetry. For this reason, it is very important to immerse the gel container in water (or surround it with water-equivalent material), at least when the normalisation irradiation is taking place. The measurement gel can then be set up without full scatter conditions, if particular density effects are being investigated.

Processes for performing and clinically implementing gel dosimetry measurements using FX gels and optical scanning systems have already been provided in the scientific literature (see for example, references [23, 25]). This note describes a particular method for obtaining accurate measurements of brachytherapy dose using optical CT scanning, despite the use of optically opaque needles. This method could be easily extended to measure dose in the presence of density heterogeneities and therefore has the potential to be particularly valuable when evaluating new brachytherapy dose calculation algorithms or commissioning new applicators. Cavities could be set into the gel, using purpose-designed and 3D printed moulds, filled with refractive-index matched fluid during pre and post-irradiation scanning, and filled with high or low-density materials (including air) or replaced with brachytherapy applicators during irradiation, and then the resulting three dimensional dose measurement could be compared with brachytherapy dose calculations generated using the TG-43 algorithm or model based dose calculation algorithms (MBDCAs) [29]. Accurate 3D gel measurements could make an important contribution to the existing literature on MBDCAs [6, 30–32] and would provide useful information on dosimetric uncertainties in regions close to density heterogeneities for users of TG-43 based systems.

Conclusion

This study demonstrated a practical method for using optical CT scanning of a Fricke gel, to obtain accurate three-dimensional dose measurements around complex HDR brachytherapy implants. Accurate and detailed results can be obtained by creating purpose-built gel containers in order to ensure precise positioning and alignment of brachytherapy needles, removing the catheters or needles prior to optical CT scanning and filling the resulting voids with refractive index matched fluid to avoid the effects of missing-ray sum data arising from the presence of opaque objects in the optical scanning path, and otherwise planning and delivering the HDR brachytherapy treatment as usual. By these means, relatively noise-free three-dimensional dose distributions can be produced, even when relatively low prescription doses are used, with an accuracy within 1% at distances greater than 0.1 cm from the source.

The phantom construction and optical CT scanning method proposed in this work has the potential to enable the use of optically scanned Fricke gels (and other gels) to be used for routine quality assurance measurements of complex HDR brachytherapy treatment deliveries, via accurate, high-resolution, three-dimensional dose measurements.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human and animal participants This article does not contain any studies with human participants or animals performed by any of the authors.

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