A Practical Use for FXG Gel Dosimetry

T Olding1, G Salomons2, J Darko2 and L J Schreiner1,2
1Department of Physics, Queen’s University, Kingston, Ontario, Canada, K7L3N6
2Cancer Centre of South Eastern Ontario at Kingston General Hospital, 25 King Street West, Kingston, ON, Canada, K7L5P9
E-Mail: Tim.Olding@krcc.on.ca

Abstract. In-phantom Fricke-xylenol orange-gelatin (FXG) gel dosimetry yields three dimensional (3D) dose data for intensity modulated radiation therapy (IMRT) treatment plan verification within 18-24 hours from the point of request. The information obtained from a 3% dose difference, 3 mm distance-to-agreement gamma function comparison between treatment plan dose and gel-measured dose then provides a useful secondary 3D quality assurance check of the treatment plan prior to delivery.

1. Introduction
Quality assurance (QA) in IMRT is important. While two dimensional (2D) and electronic portal image device (EPID) 3D techniques are quick and powerful, they can fail. Then what? Do we use gels? This paper presents an example of the application of FXG gel dosimetry [1] in combination with cone beam optical computed tomography (CT) for IMRT treatment plan evaluation [2] when a standard IMRT QA has failed. The investigation makes use of previous work related to scanner characterization [3]. A calibration basis for this FXG-gel based IMRT evaluation (megavoltage range energy independence, dose calibration linearity and intra-batch reproducibility of the FXG dosimeter) is outlined in a companion paper in these proceedings. With this background, a head-and-neck IMRT plan evaluation using a standard FXG gel-filled 1 L polyethylene terephthalate (PETE) jar-in-phantom is described.

2. Experiment
2.1. IMRT Treatment Plan Quality Assurance
Figure 1a shows a CT slice of a selected head-and-neck case at the Cancer Centre of Southeastern Ontario (CCSEO), including the overlaid planning target volume (PTV) isodose contours from the 7 field, 6 MV IMRT treatment plan calculated in Eclipse™ (Varian Medical, Palo Alto, CA, USA). Two checks were employed for treatment plan QA. First, the individual fields of the plan were cumulatively delivered at a gantry angle of 0° to an ImRT Matrixx running software version 1.6 (Scanditronix Wellhöfer, Bartlett, TN, USA). The Matrixx consists of 1020 vented ion chambers in a 32 by 32 square grid, with 7.6 mm spacing-between chambers, and the treatment unit was a Varian Clinac 21iX linear accelerator with cone beam CT (CBCT) On-Board Imaging (Advanced OBI). The aggregate Matrixx measured dose was then compared to the aggregate Eclipse plan dose using a two dimensional (2D) Low’s gamma function evaluation [4] with 3% dose difference and 3 mm distance-to-agreement criteria. The 2D gamma map (figure 1b) indicated full agreement (i.e. gamma value < 1)
Figure 1: (a) A sagittal slice of a selected head-and-neck cancer case, showing the PTV isodose contours from the calculated IMRT treatment plan in Eclipse. (b) A gamma map comparison using 3%, 3mm evaluation criteria of the aggregate Eclipse plan and Matrixx measurement dose for the treatment plan fields delivered at a gantry angle of 0°.

In the second QA check, portal image data was acquired from the delivery of the IMRT plan at the treatment unit without the patient in place. A back-projection technique-based software package (termed ‘Epidose’) [5] was then used to reconstruct 3D dose to a virtual phantom on the treatment couch (see figure 2a). The plan dose and Epidose-measured dose were compared within the software using the weighted dose difference chi ($\chi$) test described by Bakai et al [6], with 4% dose difference and 4 mm distance-to-agreement criteria. Referring to figure 2b, the agreement between plan and measured dose in the high dose region ($\geq$ 80% of the normalized prescription dose) was 78.3%, falling short of the QA target value of 80%. The agreements within the phantom PTV and body contours were 31.8% and 98.7% respectively. When the criteria were tightened to the preferred metrics of 3% and 3 mm, the agreement within the high dose region was reduced to 46.0%.

Figure 2: (a) An axial slice of the Epidose reconstructed dose distribution. The PTV and body contours are indicated on the slice and the colour bar indicates the measured dose in cGy. (b) The 4%, 4 mm $\chi$ test results for the axial slice in (a).
2.2. FXG Gel Dosimetry

FXG gel dosimeters were prepared according to the recipe outlined by Babic et al. (2008), with final concentrations of 0.3 mM ferrous ammonium sulphate (Cat.No.203505, Sigma-Aldrich Ltd., Oakville, ON, Canada), 0.05 mM xylenol orange (Cat.No.398187, Sigma-Aldrich Ltd), 65 mM sulfuric acid (Cat.No.258105, Sigma-Aldrich Ltd), and 6 wt% gelatin (Cat.No.G2500, Sigma-Aldrich Ltd) in distilled, de-ionized water. After preparation, the heated formulations were poured into 1 L PETE jars and allowed to set overnight in a refrigerator prior to irradiation.

Three dimensional imaging of the dosimeters was performed at a wavelength of 590 nm using the Vista™ cone beam optical CT scanner (Modus Medical Devices, Inc., London, Canada) [3]. Depth fiducials were marked on the surface of the PETE jars in permanent red marker, serving as reference points for registration of depth dose to attenuation in the reconstructed optical CT image.

A wax-filled reproduction of the head-and-neck from a Kyoto SBU-4 Rando anthropomorphic phantom (Capintec, Ramsey, NJ) was prepared at the CCSEO for the IMRT study, with a custom cavity designed to fit the standard 1 L PETE jar-sized dosimeter (figure 3a). Two 1 L PETE containers were filled from a single batch of gel. One container was irradiated with a well characterized 12 MeV electron beam using the Varian Clinac 21iX linear accelerator (figures 3b and 3c) and used for dose-to-attenuation calibration. The other container was inserted into the wax-filled Rando reproduction as the IMRT measurement dosimeter. A CT data set was acquired with a FXG gel dosimeter ‘blank’ inserted in the phantom cavity on a Picker PQ 5000 Philips CT scanner (Philips Medical Systems, Andover, MA, USA). Fiducial marks were added to the exterior surface of the wax-filled reproduction as reference points for positioning at the treatment unit.

The wax Rando CT was first registered to the patient CT in Eclipse. The Matrixx and Epidose-evaluated IMRT treatment plan was then applied to the phantom CT data set and a single fraction (prescription dose of 200 cGy) scheduled to the treatment unit. CBCT imaging of the phantom was completed at 1 mm cubic voxel resolution according to the standard head protocol (100kVp/145mAs, half scan with full bowtie filter), and 3D-3D planning CT-onboard CBCT matching was performed. The planned treatment fraction was then delivered to the phantom.

Optical CT gel-measured dose data were registered to the Eclipse plan data in MatLab (Mathworks, Newark, NJ, USA), for viewing in the Computational Environment for Radiotherapy Research (CERR) developed at Washington University (St Louis, MO, USA) [7]. Prior to irradiation, a red marker was used to indicate fiducials on the surface of the PETE jar, to fix the spatial position of the optical CT volume data. Two sets of three fiducials marked on separate parallel planes were adequate

Figure 3: (a) A wax-filled reproduction of the head and neck from a Kyoto SBU-4 Rando anthropomorphic phantom (Capintec, Ramsey, NJ) prepared at the CCSEO, with a cavity for insertion of a gel-filled 1 L PETE jar. (b) Another view of the wax Rando reproduction, with a measurement jar for a test IMRT plan on the right, and an electron beam-irradiated FXG gel calibration jar on the left. (c) The calibration gel dosimeter electron beam setup at the treatment unit.
for this purpose. Steel 1 mm diameter beads were affixed with tape on top of the permanent marker fiducials to provide positioning information from the 3D-3D planning CT matched onboard CBCT scan. The beads were removed from the jar after the irradiation, before optical CT scanning. An in-house registration routine written in MATLAB [8] was used to align the optical CT and CBCT fiducial data points through an affine transformation solid body rotation, and register the optical CT dose data to the planning CT. The mean CBCT scan dose to the gel dosimeter was determined by ion chamber measurements as 0.8 ± 0.1 cGy, and was appropriately accounted for. Dose evaluations between the reference Eclipse planning dose and optical CT gel-measured dose were completed using in-house developed routines in MatLab and contouring tools in CERR for full 3D voxel-by-voxel Low’s gamma function analysis [8].

Figure 4a shows 3D visualizations (in CERR) of the treatment plan (top) and gel-measured dose distributions (bottom) overlaid on the contoured planning CT images for the 7 field, 6 MV, 200 cGy (single fraction) IMRT treatment plan delivery. Figure 4b presents the results of a 3D Low’s gamma function voxel-by-voxel comparison of gel-measured dose against the reference Eclipse dose for the IMRT delivery, employing 3% dose difference and 3 mm distance-to-agreement criteria. The percentage of treatment plan dose and measured gel dose voxels in agreement (i.e. gamma value less than 1) within the dose evaluation volume covering the central 8 cm in diameter and 10 cm in height of the jar was 99.7%.

![3D visualizations](image1)

**Figure 4:** (a) Eclipse treatment planning dose (top) and gel-measured dose (bottom) for the 7 field, 6MV 200 cGy IMRT plan delivered to the wax-filled Rando reproduction. (b) A Low’s gamma function comparison (3%, 3mm) between reference treatment planning dose calculated in Eclipse™ and FXG gel-measured dose.

3. Discussion & Conclusions

More than 90% of the IMRT treatment plan evaluations completed at the CSSEO to date have satisfied the agreement criteria between Eclipse plan dose and Epidose-measured dose, and hence have not required additional QA and/or re-planning. In this particular head-and-neck case, however, the χ test indicated significant disagreement between the plan and the measurement. The alternative 3D dose check using FXG gel dosimetry indicated, on the other hand, that the plan delivery yields an acceptable dose distribution in the phantom within 3%, 3 mm gamma comparison criteria. Given a total gel preparation time of 12 hours or less, CT acquisition and plan registration less than 1 hour, scan and reconstruction time under 30 minutes and analysis time of 3-4 hours, the 3D dose verification was easily completed within 18-24 hours from the point of request.
This illustrative example underscores the relevance of 3D dose verification for complex IMRT treatment plans. The 3D Epidose data indicated a problem with the delivery of this particular plan that did not show up in the 2D Matrixx check. Following the initial evaluation, the Epidose QA process was repeated on a separate occasion, with a comparable failed outcome. While the cause of disagreement in this particular case has not as yet been determined, similar occasional unexplained failures of Epidose tests in clinical practice have been reported [5].

The in-phantom FXG gel dose measurement subsequently indicated (in a timely manner) that the IMRT treatment plan was acceptable. These results lead to some questions. First of all, do we believe the gel measurement? And, if we do believe the gel measurement, how do we explain the Epidose data? Finally, and perhaps most importantly, does the 3D dose data from gel dosimetry lend the necessary confidence to proceed with this course of treatment? The experience reported here has prompted further validation of the Epidose analysis beyond the ion chamber and film commissioning already performed. Phantoms have been built to enable direct gel-based measurement of complex 3D distributions in the Epidose cylindrical geometry.

The authors suggest that FXG gel dosimetry can gain the necessary degree of confidence to make a significant contribution to IMRT QA, as it builds up a track record of careful usage in clinically relevant cases. The data in this report indicates that FXG gel dosimetry is capable of providing a useful secondary 3D measure of IMRT treatment plan dose. But a single case study is not enough to warrant further conclusions. We need to regularly engage in the sideline activity of using gel dosimetry for selected clinical plan evaluations with the clear understanding that a deeper case history will help to establish gel measurement as one of the available tools in the quality assurance decision-making process.

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