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Reconstructing 3D x-ray CT images of polymer gel dosimeters using the zero-scan method

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Abstract. In this study x-ray CT has been used to produce a 3D image of an irradiated PAGAT gel sample, with noise-reduction achieved using the ‘zero-scan’ method. The gel was repeatedly CT scanned and a linear fit to the varying Hounsfield unit of each pixel in the 3D volume was evaluated across the repeated scans, allowing a zero-scan extrapolation of the image to be obtained. To minimise heating of the CT scanner’s x-ray tube, this study used a large slice thickness (1 cm), to provide image slices across the irradiated region of the gel, and a relatively small number of CT scans (63), to extrapolate the zero-scan image. The resulting set of transverse images shows reduced noise compared to images from the initial CT scan of the gel, without being degraded by the additional radiation dose delivered to the gel during the repeated scanning. The full, 3D image of the gel has a low spatial resolution in the longitudinal direction, due to the selected scan parameters. Nonetheless, important features of the dose distribution are apparent in the 3D x-ray CT scan of the gel. The results of this study demonstrate that the zero-scan extrapolation method can be applied to the reconstruction of multiple x-ray CT slices, to provide useful 2D and 3D images of irradiated dosimetry gels.

1. Introduction

Three dimensional readout of dosimetry gels irradiated with radiotherapy beams has been achieved using a range of imaging modalities. Magnetic resonance imaging (MRI) [1, 2] and optical CT imaging [3, 4] are a well-established techniques for providing low-noise, high-resolution 3D images of irradiated gels, but MRI and optical CT systems are not often available in radiation oncology departments. By contrast, obtaining good quality 3D images of irradiated gels using x-ray CT [5, 6] and ultrasound [7] imaging systems remains challenging, although advantageous given the frequent availability of these systems in radiation oncology departments.

The usefulness of x-ray CT for dosimetry gel readout has been limited the small change in gel density with irradiation [6, 7], which results in a weak image signal that is easily overwhelmed by noise. Noise in x-ray CT images can be reduced by averaging over repeated scans, but this technique results in a loss of dosimetric fidelity as the gel is further irradiated by each successive CT scan.

Recently this issue has been addressed by the introduction of the ‘zero-scan’ method [8], summarised below, which has been shown to substantially reduce the noise in a single slice (2D) x-ray

CT image of a PAGAT gel sample [8]. The aim of the current study is to further examine the zero-scan method and to establish its utility for producing noise-reduced x-ray CT images of dosimetry gels in three dimensions. In this work we extend the zero-scan method to a multi-slice dataset.

2. Methods and Materials

The zero-scan method involves the repeated x-ray CT scanning of an irradiated gel sample. As the gel absorbs and reacts to the compounding x-ray scanning dose, the Hounsfield unit of each pixel in the resulting images slowly increases [8]. A linear fit for Hounsfield unit versus scan number is then evaluated across the repeated scans and, for each pixel, this linear fit is extrapolated back to the zero, producing the 'zero-scan' image of the gel.

For this study, a PAGAT gel sample was prepared according to the recipe reported by Venning *et al.* [9], with an increased Tetrakis (hydroxymethyl) phosphonium chloride (THPC) concentration as recommended by Khoei *et al.* [10], and set in a 10 cm high, 7 cm wide, cylindrical polyethylene terephthalate (PET) container. The gel was stored for 18 h at 4 °C before irradiation.

The gel sample was irradiated using a Varian iX linear accelerator (Varian Medical Systems, Palo Alto, USA), producing a nominal 6 MV photon beam at a dose rate of 600 MU/min dose rate. The treatment delivered to the gel consisted of three dynamically wedged fields [11], with a maximum dose of 6 Gy. The gel was then returned to storage at 4 °C.

The x-ray CT of the gel was carried out 6 h after irradiation. The gel was scanned 63 times using a GE Lightspeed RT 4 CT scanner (GE Healthcare, Waukesha, USA) with an x-ray tube load of 230 mA with a 1 s rotation, a nominal tube energy of 120 kVp, and 4×1 cm slices. A total of 12 contiguous 1 cm images scanned with a 25 cm Scan field of view and reconstructed on a 512×512 pixel image matrix.

Before performing the zero-scan extrapolation, each image of the irradiated gel was first corrected using the image subtraction protocol developed by Trapp *et al.* [6]. The CT data was imported into Matlab (version 7.8.0.342, The MathWorks, Natick, MA) for further processing. The linear $12 \times 512 \times 512$ linear fits required by the zero-scan method were obtained by applying a linear fit using the inbuilt *Polymfit* function to each pixel in the 3D data set [8].

3. Results

Transverse images of the six central slices in the irradiated region of the gel (slices 4-9) are shown in figure 1, with and without the use of the zero-scan method. The zero-scan images show a clearer signal with less noise than the raw images. The locations, orientations and overlaps between the radiation beams can be clearly identified in all of the zero-scan images, while this information cannot be easily obtained from the raw images.

Figures 2(a) to (f) show slices through the zero-scan 3D image of the gel, in the coronal, transverse and sagittal planes. The low resolution of the coronal and sagittal images arises from the 1.0 cm CT slice thickness used to obtain the data. Despite the low resolution of these images, it is nonetheless possible to observe the different intensities of the irradiated regions in the gel in figures 2(a) to (f): Region A was irradiated with one beam. Region B was irradiated with an opposed pair of beams. Region A+B was irradiated with all three beams.

It is evident from the grey scale values shown in figures 2(a) to (f), where regions of low dose appear darker than regions of high dose, that region A received a lower dose than region B, which received a lower dose than region A+B. It is also apparent, although less obvious, from an examination of figures 2(a) to (f), that in the coronal and sagittal images, the direction of dynamic wedge motion direction is up the page, with the thin edge of the wedge at the bottom of the page and the thick end of the wedge at the top of the page. In the transverse image, the wedge motion direction is into the page.

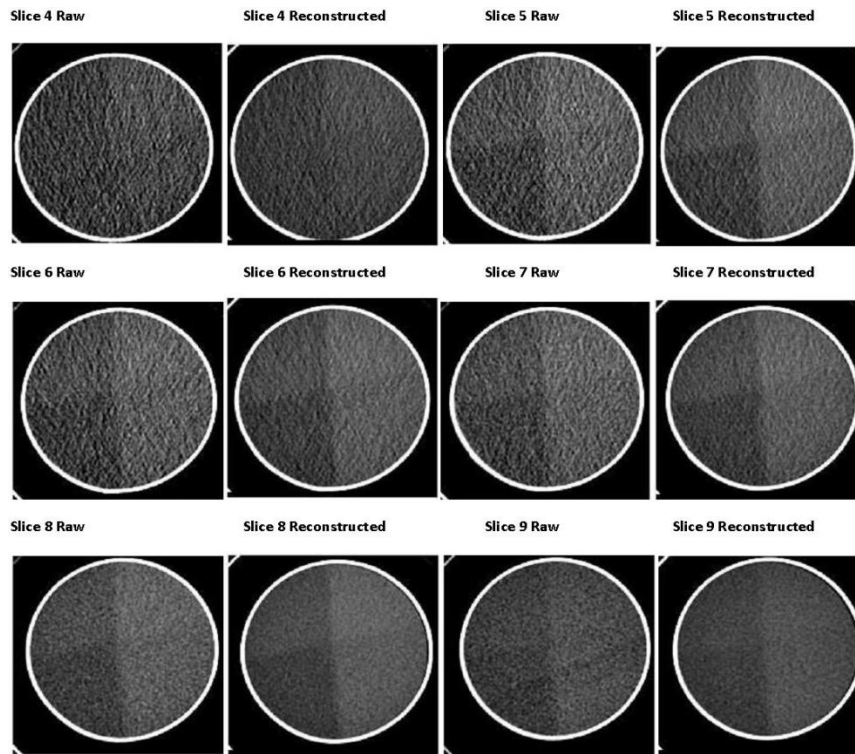


Figure 1. Image slices reconstructed with (right hand image in each pair) and without (left hand image in each pair) using the zero-scan method.

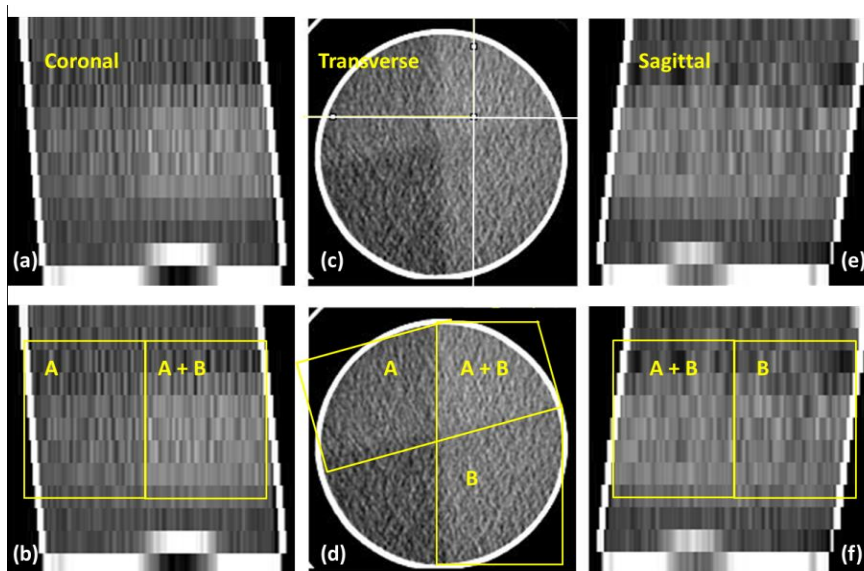


Figure 2. Coronal (a) and (b), transverse (c) and (d) and sagittal (e) and (f) views, through the zero-scan 3D image of the gel. White lines in (c) indicate the positions of the coronal (horizontal line) and sagittal (vertical line) planes shown in (a) and (e), respectively. Images (b), (d) and (f) are duplicates of (a), (c) and (e). Regions A, B and A + B are described in the text.

4. Discussion and Conclusion

The transverse plane images shown in figure 1 confirm previous observations [8], indicating that the zero-scan method can produce x-ray CT images with reduced noise compared to images from the initial CT scan of the gel. While the noise in the zero-scan images is reduced, the image intensity is unchanged, indicating that the dosimetric accuracy of the zero-scan images has not been degraded by the additional radiation dose delivered to the gel during the repeated scanning.

The full, 3D image of the gel has a low spatial resolution in the longitudinal direction, due to the selected scan parameters. Nonetheless, important features of the dose distribution, including the locations of the beams and the orientations of the dynamic wedges are apparent in the 3D x-ray CT scan of the gel.

Higher-resolution images of dosimetric gels could be potentially be obtained by using a smaller slice thickness and the noise in these images could be further reduced by performing additional CT scans and obtaining the zero-scan images from a fit to a larger data set, as shown for Kakakhel *et al*'s single-slice scan [8].

The results of this study demonstrate that the zero-scan extrapolation method can be applied to the reconstruction of multiple x-ray CT slices, to provide useful 2D and 3D images of irradiated dosimetry gels. Such detailed dosimetric information could be used to verify the accuracy and deliverability for more-complex plans such as stereotactic [4], intensity-modulated or dynamically wedged radiotherapy treatments [11].

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