High dose rate brachytherapy three-dimensional gel dosimetry using optical computed tomography readout

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Abstract. The cause and removal of streaking artifacts from catheters within radiochromic 3D dosimeters was investigated to allow the use of these dosimeters for high dose rate (HDR) brachytherapy applications. The OSC-TV iterative reconstruction algorithm’s ability to remove the streaking artifacts from one or more catheters was validated using external beam irradiations and leuco crystal violet (LCV) micelle gels. One and two catheter HDR plans were then delivered to LCV gels. Dose volumes from the gels were reconstructed with the OSC-TV algorithm, calibrated, and registered to treatment planning system dose volumes, and were shown to be artifact free and in agreement with the expected values.

1. Introduction

Three-dimensional (3D) dosimetry has become more easily accessible because of the development of optical computed tomography (optCT) gel scanners, which are less costly when compared to x-ray CT or magnetic resonance imaging (MRI) scanners [1]. The use of radiochromic dosimeters with optCT readout for quality assurance (QA) of external beam radiation therapy has become commonplace, with developments such as improved scanners, reconstruction algorithms, radiochromic gels and plastics, and analysis software, making the QA process with gel dosimetry faster and more accurate.

Despite the progress in the field of 3D dosimetry, most applications remain within external beam radiotherapy (EBRT), while applications in high dose rate (HDR) brachytherapy are limited. Work with polymer-based and Fricke gels with MRI read-out for brachytherapy dosimetry has shown promising results [2-5], but the barrier to entry for clinical use is high [6]. Work using radiochromic 3D dosimeters with optCT readout has also shown promise [7-9], but streaking artifacts radiating from the inserted catheters created during the dose volume reconstruction can leave sections of the volume unusable for dosimetry. In this work we report on efforts to use iterative reconstruction algorithms to extend the readable volume of the dosimeter when catheters are present. It is anticipated that this work will allow for patient specific QA for HDR brachytherapy and eventually possible HDR source characterization. Patient specific QA has been adopted for EBRT as a standard of care in many clinics, but has not been adopted for HDR brachytherapy. This work seeks to improve 3D gel dosimetry for HDR brachytherapy to provide a dosimetry technique for patient specific QA for HDR brachytherapy.

In 3D dosimetry optCT, change in attenuation (Δμ) from pre to post-irradiation is found at each voxel rather than optical attenuation values (μ). This is accomplished by capturing projection images before and after irradiation, and performing the reconstruction using the ratios of the pre and post-irradiation images. With this in mind, it would stand to reason that any catheters within an imaged gel would not
change in attenuation, and so should “disappear” when the ratio of pre and post-irradiation images are taken, and reconstruction results should not be effected. This is not the case in practice however, and so the cause of this effect will first be investigated.

The reduction or removal of streaking artifacts in CT reconstructions with the use of iterative reconstruction algorithms instead of the traditional filtered-backprojection type algorithms has been shown in the field of x-ray CT [10]. These iterative algorithms are more computationally intensive than filtered-backprojection algorithms, but the use of graphics processing units (GPUs) to cut computation times makes it possible to now use the algorithms practically. Such iterative algorithms, in particular the Ordered Subsets Convex algorithm with Total Variation minimization regularization (OSC-TV), have been applied to optCT [11, 12]. The OSC-TV algorithm has been used to reduce noise and jar wall artifacts, but has not yet been applied to removing streaking artifacts from catheters. It is investigated here to characterize its ability to remove the streaking artifacts found in brachytherapy applications.

2. Materials and Methods

All the gels used in this study were leuco crystal violet (LCV) micelle gels prepared according to the recipe of Babic et al [13], which respond linearly to dose, are free from dose-rate or energy dependence, and do not suffer from spatially instability resulting from diffusion [13]. The LCV micelle gel recipe has low dose sensitivity, and so the irradiations delivered were above the clinical range (80Gy at 1cm from the HDR source axis). The results presented here are applicable not only for the gels used, but for all types of 3D radiochromic dosimeters. Gels that required catheters to be inserted were prepared by suspending the catheters within the gels as they set using special lids or plastic films over the jar that held the catheters in place (Figure 1). Once the gel was set, the catheters would be cut such that the jar lid could be fastened, allowing the gel to be optically scanned.

In order to investigate the use of the OSC-TV algorithm for artifact removal, the algorithm was first validated using irradiations that have been well characterized (e.g. external beam radiation). To characterize the artifact removal, two gels received an identical irradiation (two perpendicular beams); one gel containing an inserted catheter and the other no catheter. The gel with the catheter had its dose volume reconstructed via the OSC-TV algorithm, while the gel without the catheter was reconstructed via a gold-standard filtered-backprojection algorithm. The reconstructed dose volumes were then compared to characterize the OSC-TV algorithm’s artifact removal capabilities. This also allowed the strength of the noise reduction of the OSC-TV algorithm to be “tuned” to ensure it did not blur sharp dose gradients.
With the OSC-TV algorithm verified, gels were prepared with one or two catheters inserted. The gels were then imaged with x-ray CT (1mm slice thickness, 0.3mm spacing) using a Phillips Brilliance Big Bore CT scanner (Philips Medical Systems, Cleveland, OH). Guidewires were inserted into each catheter during imaging to allow for tracking of the catheters during planning (figure 2). X-ray CT and matching optCT fiducials (metal BBs and black marker spots) were also placed on the jar to allow for the registration of treatment planning and gel dose volumes. Once imaged, catheter tracking, treatment planning, and dose calculation were performed within the Oncentra Brachytherapy treatment planning system (TPS) (Elekta Ltd., Stockholm, Sweden). During irradiation, the gels were placed within a custom PMMA phantom and then the catheters were connected to a Flexitron Remote Afterloader and were irradiated with a Flexisource Ir$^{192}$ source (Elekta Ltd., Stockholm, Sweden) (figure 3).

In order to calibrate the gels for dose comparisons, the gels were made in batches, with one gel reserved for calibration. This gel received an electron-beam irradiation following the protocol from Alexander et al [14], and was analyzed in 3DSlicer (www.slicer.org) using the 3DSlicer Gel Dosimetry Analysis slicelet. This slicelet was also used for dose volume registration and comparison.

The gels were scanned pre and post-irradiation with the Vista 15 cone-beam optCT scanner (Modus Medical Devices Inc., London, ON) in a refractive index matched solution under amber light, with 410 projections recorded per scan. Flood field projections were also captured by filling the scanner tank fully with the matched solution. Filtered-backprojection reconstructions were performed using the VistaRecon software provided with the Vista 15 scanner. OSC-TV reconstructions were performed by using an in-house open-source computed tomography reconstruction toolkit (https://github.com/DavidADeVries/Gyrfalcon-CT-Simulation-And-Reconstruction) programmed in MATLAB (The Mathworks, Inc., Natick, MA). GPU acceleration of the OSC-TV algorithm was achieved using functions from the open-source TIGRE toolkit [15]. All reconstructions were computed at the same resolution of a 256×256×256 voxel data set with 0.5×0.5×0.5mm voxels.

3. Results and Conclusions

3.1. Cause of streaking artifacts
The cause of the streaking artifacts was found to be partly from a misalignment of the imaged catheter in the pre and post-irradiation projection images. As shown in figure 4a-b, the pre and post irradiation projections clearly show the catheter, but when the ratio of the projections is taken (figure 4c) the catheter does not “disappear” as expected. Instead two lines, one dark and one light are shown, pointing to a shift between the projections. This is due to the limitation of being able to reproducibly position the gel within the optCT scanner, since the gel is aligned within the scanner by lining up a visual marker with the jar clamp. By comparing figure 5b and 5d it is clear that taking the ratio of the projections reduces the streaking artifacts, but does not remove them, motivating the need to use the OSC-TV algorithm. Perfect alignment of the projection images may not necessarily eliminate the artifacts either, as photon starvation or scattering effects may also produce artifacts.

![Figure 4](image_url)

**Figure 4.** Natural logarithm of the ratio of (a) flood field and pre-irradiation, (b) flood field and post-irradiation, and (c) pre and post-irradiation projections from an external beam irradiation. The inset in (c) shows the misalignment of the catheter between the pre and post-irradiation projections.
3.2. **OSC-TV reconstruction algorithm validation**

The OSC-TV algorithm was validated for removing the streaking artifacts by using the algorithm to reconstruct dose volumes for gels with inserted catheters that had been irradiated with external beam radiation, and comparing these results against a gel with no inserted catheters that had received the identical irradiation. The results of one such trial are shown in figure 5, demonstrating the ability of the OSC-TV algorithm to remove the streaking artifacts, as well as reduce noise, without compromising the accuracy of the dosimetry results. The trials also found that within a 5mm radius of any catheter, the results of the OSC-TV algorithm has a high uncertainty, and so dosimetry within this range is not yet possible.

These validation trials also motivated modifying of the OSC-TV algorithm from its original implementation following the results of trials with multiple catheters in the gels. During these trials new artifacts appeared that joined the catheters (figure 7c), due likely to the inability of the optical attenuation model of the reconstruction algorithm to model the joint attenuation of multiple catheters. To combat this effect, the voxels containing the catheters were first found by thresholding the pre-irradiation projection images, such that only the highly attenuating catheters were set to “1” and all other pixels were set to “0”, and preforming a single reconstruction iteration. All rays passing through these catheter voxels would then be rejected from the reconstruction process, which is allowable in iterative reconstructions which do not require symmetric projection data sets. This modification of the algorithm effectively removed the new artifact and was used for all results presented.

3.3. **Brachytherapy dosimetry results**

Two HDR brachytherapy deliveries were measured using the LCV micelle gels and OSC-TV reconstruction algorithm. The first consisted of a single catheter with a single dwell position. The comparison of the expected dose volume from the treatment planning system to the calibrated gel dose volumes reconstructed by the filtered-backprojection and OSC-TV algorithms are shown in figure 6.

![Figure 5](imageURL)

**Figure 5.** Axial slices of a dose volume reconstruction of an identical external beam irradiation delivered to two gels. The first gel (a) had no catheter inserted and was reconstructed using filtered-backprojection. The second gel had one catheter inserted and was reconstructed using filtered-backprojection (b), the OSC-TV algorithm (c), and filtered-backprojection with only using post-irradiation projection images (d). (e) shows a line profile across the catheter, demonstrating the artifact removal and noise reduction in (c) without compromising accurate dosimetry.
The modified OSC-TV algorithm is shown to remove all the artifacts present in the filtered-backprojection reconstruction, as well as to have close agreement to the TPS.

**Figure 6.** Axial slices of dose volumes of a single dwell position irradiation from the TPS (a), and from volumes reconstructed by filtered-backprojection (b), and OSC-TV (c). The line profiles through the catheter (d) and near the catheter (e) show the agreement between (a) and (c) and the effect of the streaking artifacts in (b). The TPS dose calculation cuts-off within 3mm of the source, causing the flattened profile in (d).
The second brachytherapy delivery consisted of two catheters with five equally spaced and timed dwell positions along each catheter. As shown in Figure 7, the comparison between the TPS and OSC-TV reconstructed dose volumes shows close agreement. However, the apparent shift of the right-most dose peak in figure 7 that is not present in the left-most peak points to one of the catheters shifting between x-ray CT imaging and plan delivery. This is most likely due to the strain put on the catheters will being secured to the afterloader.

Planned future studies using the OncoSmart Catheter System (Elekta Ltd., Stockholm, Sweden) will aim to avoid placing strain on the catheters during irradiation. The OncoSmart Catheter System features a nested catheter system, allowing for an outer catheter to remain within the gel, while an inner catheter can be connected to the afterloader before being inserted into the outer catheter, avoiding any strain on the catheter in the gel.

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