A ‘quad-phantom’ film dosimeter for use as a multi-planar verification tool for PRESAGE/optical-CT

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Abstract.

Introduction: To develop and characterize the accuracy and reproducibility of a ‘quad-phantom’ dosimeter which will serve as an independent verification tool during commissioning of a PRESAGE/optical-CT 3D dosimetry system. Methods: A 16cm x 12cm cylindrical quad-phantom was constructed from four pieces of solid polyurethane mimicking the PRESAGE material. Films were placed and anchored in orthogonal planes and the quad-phantom was fastened tightly together and placed in a water-filled Styrofoam container for irradiation. A simple, two-field plan consisting of 6x6cm anterior-posterior and right-lateral 6MV photon beams (400cGy) was delivered three times (fresh films inserted for each) with a Varian Clinac 600C. Image registration was performed in the Computational Environment for Radiological Research (CERR) and dose profiles and gamma analysis was performed in CERR and MATLAB. Results & Discussion: Excellent reproducibility was observed during the irradiations, with ~2.3% standard deviation between all pixels. Using a 3%, 3mm gamma criteria, excellent dosimetric accuracy was observed, with 98.8% and 96.3% passing rates in the sagittal and axial planes, respectively. Conclusion: The preliminary results indicate that the quad-phantom can serve as a reproducible and accurate system for high resolution dosimetry in orthogonal planes and should serve as an effective verification tool for PRESAGE/optical-CT in more challenging clinical scenarios.

1. Introduction

Recently, more and more institutions are shifting towards using Gafchromic films (e.g. EBT – ISP Corporation) for high resolution two-dimensional dosimetry. EBT films are near-tissue equivalent, structurally rugged, do not require developing nor show signs of sensitivity to room light or dose-rate [1]. These films also have the same high-resolution as their radiographic predecessors and can be digitized with flatbed scanners. EBT has been used in our group for several years as an independent tool to verify PRESAGE/optical-CT dose distributions. In prior work, PRESAGE dosimeters were cut in axial sections (after all optical-CT dosimetry had been completed) to enable EBT film verification in several axial planes [2]. It was necessary to redeliver the treatment plan to the film/PRESAGE dosimeter. While effective, this process was cumbersome. Here we report a novel quad-phantom system designed to enable efficient independent verification of PRESAGE dose-distributions without the need for slicing dosimeters.
2. Methods

2.1. Construction of the quad phantom

A standard cylindrical PRESAGE dosimeter in use in our lab is a cylinder of dimensions (12cm long x 16cm diameter). The quad-phantom was designed to mimic this standard dosimeter, in both geometry and material properties (i.e. CT number). Four pieces of solid polyurethane were combined to form the cylindrical phantom as seen in Figure 1A. This arrangement enables EBT2 film measurement in both the axial and sagittal planes. Precise alignment of the quadrants was achieved utilizing small metal pins embedded into adjoining surfaces. These markers also served as registration and alignment fiducials for treatment planning. EBT2 films were cut into rectangular and circular shapes for measurements in the sagittal and axial planes, respectively (Figure 1B). Each film was pinned to its corresponding quadrants via the metal fiducial barbs. The quadrants were then fastened tightly together with polymer tape and placed within a water-filled rectangular Styrofoam container for irradiations. This was found necessary to avoid small air-gaps present at the interface. These air gaps arose because of a slight bowing of the flat surfaces of the quadrants that occurred during curing of the polyurethane. Planning studies showed that these air gaps, although small, had a noticeable perturbation on the dosimetry in the film planes.

2.2. Irradiations, registration and image analysis

The viability of the quad-phantom approach was investigated using a simple two-field irradiation for which the planning system was known to be accurate, and could therefore be used as a gold standard. The quad-phantom was irradiated three times with the two-field plan; replacing films in both planes with each irradiation. The accuracy and reproducibility of the phantom was then determined by comparing profiles and 2D gamma maps using a 3%, 3mm gamma criteria.

The two-field plan consisted of 6x6cm anterior-posterior and right-lateral 6 MV photon beams as seen in Figure 2, using a Varian Clinac 600 C/D. Unirradiated EBT2 films were ’pre’-scanned, and then inserted into the quad-phantom prior to treatment. After 48 hrs post irradiation, the films were removed and ’post’-scanned using the same protocol as follows: Portrait mode scanning was performed in RGB mode using an EPSON Perfection 4990 flatbed scanner, which captured 48 bit images with 200 dpi resolution. It has been shown that the scanner response is most uniform at its center, so all films were positioned in this fashion. Several investigators have shown that there is a warming up effect that occurs when the scanner is first turned on which could result in dosimetric inaccuracies. Likewise, studies have shown that an average of three scans improves this further [3-4]. Following these recommendations, the first two scans were ignored and then all films were scanned three times and averaged. The radiation induced change in optical density was then calculated and

![Figure 1: A) Schematic of the quadrant phantom (left). B) Four pieces of polyurethane combine with orthogonal planes of EBT2 film to form a 12x16cm cylinder (right).](image)

![Figure 2: Screenshot of the two field plan in Eclipse. This plan consisted of two 6x6cm, 6MV photon beams in the anterior-posterior and right-lateral directions with a 400 cGy prescription dose.](image)
converted to dose maps using a calibration curve.

The scanned film images (tiff format) were imported into MATLAB for processing purposes. Raw, red-channel pixel data was extracted from each tiff image and converted to optical-density values. Images were corrected for scanner non-uniformity on a pixel-by-pixel basis using a red-channel correction matrix generated each time by the pre-scan film. Change in optical-density was calculated and converted to absolute dose by a calibration curve. Image registration was performed in the Computational Environment for Radiological Research (CERR) using the DICOM files from Eclipse and the dose maps from MATLAB.

3. Results & Discussion

The reproducibility of the quad-phantom measurements, as determined from the three repeat independent irradiations, is shown in Figure 3. Horizontal dose profiles were taken through the central portion of the axial plane films, registered together and plotted. In addition, percent standard deviation was determined for each pixel and an average was determined over the entire surface. There was excellent precision in the results from all three irradiations, with ~ 2.3% variation between all films. This was a promising result for many reasons. Since the phantom had to be removed from the water each time and completely disassembled, there is uncertainty introduced when replacing the film and re-taping the quadrant. In addition, there is error introduced with the alignment of the phantom in the water. There are also uncertainties introduced with the scanning protocols, in terms of scattering properties from alignment and orientation on the scanner glass. It was encouraging to see that even with a combination of all of these sources of error the system seems to perform fairly consistent over time.

The accuracy of the quad-phantom dosimetry was evaluated by comparison to the Eclipse treatment planning system. Several dose profiles were produced from fully registered film/plan combinations in both planes, as seen in Figures 4 and 5. Excellent agreement, (within 2%) was observed in both planes. The noise in the film data was slightly higher and may be attributed to the inherent scanner-induced effects listed in the previous paragraph, along with surface defects on the film. These defects were observed prior to irradiation in almost all films and may have also been created when the films were placed between the polyurethane layers.

Figure 3: Horizontal Profile Comparison of 3 independent quad-phantom measurements of the Two Field Plan. This illustrates the high level of reproducibility (within 2%) in the setup and irradiation of the quadrant phantom. This required a complete re-setting of the dosimeter in the water, along with the positioning of the film and scanning of the film. These results are promising considering the sources of error involved.

Figure 4: Vertical Profile in the Sagittal Plane. This screenshot, taken from CERR, is evidence that the dose measured with the rectangular film (green) is highly consistent with that of the Eclipse plan (orange).
2D gamma maps were also created using the Normalized Dose Distribution [5], and are shown in Figures 6 and 7. Using the same (3%, 3 mm) criteria that is often used in clinical scenarios, excellent agreement was seen between the films and the treatment planning system, with passing rates of 96.3% and 98.8% in the axial and sagittal planes, respectively. Visual inspection of the circular film suggests that the majority of the failing occurs at the interface between the beam and quadrant. This could be attributed to light scattering at the edges of the film during scanning. Scattered light may cause an artificially higher optical density region in this area, indicating higher dose. This would correlate with the “hotter” areas of failing that occur when the plan is used as the reference and the film as the calculated value during the NDD analysis. This may have contributed to the failing of the anterior-posterior beam interface as well, which is also witnessed in the rectangular film.

Figure 5: Horizontal Profile in the Axial Plane. Likewise, the dosimetric accuracy of the circular film (green) is high when compared to the Eclipse plan (orange).

Figure 6: A 2D Gamma Map comparison of Eclipse and EBT2 in the Sagittal Plane of the quad-phantom irradiated with the 2 field plan. Using a (3%, 3mm) criteria, 2D gamma analysis was performed between the EBT2 film (left) and Eclipse plan (right), using Eclipse as the reference. A passing rate of 98.8% was observed. Of the points that failed the gamma criteria, 98.5% were hot (i.e. EBT2>Eclipse) as indicated in red, and 1.5% were cold as indicated in blue.
The three independent quad phantom irradiations demonstrated a high level of reproducibility and accuracy when compared to the treatment planning system: with 98.8% and 96.3% passing rates in the sagittal and axial planes respectively, when (3%, 3mm) gamma criteria were used. In addition, this system provides a high level of reproducibility, with an average (~2.3%) standard deviation over all pixels. The quad phantom is anticipated to serve as an effective orthogonal plane verification tool for independent verification of our PRESAGE/optical-CT system.

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