Validation of spine SBRT using a 3D printed Anthropomorphic phantom

KH Dekker¹, KM Alexander¹, F Ynoe de Moraes¹,², T Olding¹,²,³
¹Cancer Centre of Southeastern Ontario at Kingston General Hospital, 25 King Street West, Kingston, ON, K7L 5P9, Canada
²Department of Oncology, Queen’s University, Kingston, ON, K7L 3N6, Canada
³Department of Physics, Queen’s University, Kingston, ON, K7L 3N6, Canada

E-mail: kurtis.dekker@kingstonhsc.ca

Abstract. A segment of a spine was 3D-printed based on real patient anatomy, using metal-doped high density plastic to radiographically mimic bone. This spine was submerged in a water tank to create an anthropomorphic phantom. The spine print incorporated a slot for Gafchromic EBT3 film dosimeters and fiducials for alignment of measured and calculated dose distributions. Spine SBRT treatment plans were generated for both 6 MV and 10FFF energies based on oncologist-drawn contours transferred from real anatomy. Plans were delivered under image guidance using our clinical procedures, to evaluate the dosimetric accuracy of our planning system in high density inhomogeneities and the geometric accuracy of delivery. Results show that the Acuros XB algorithm (dose-to-water) agrees well with film measurements throughout the measured region, including within the bone substitute material. Alignment of the steep dose gradients in planned and measured doses was within 0.5 mm in the ANT-POST direction and within 0.9 mm in the SUP-INF direction, both within machine tolerances. Our results give us confidence in our ability to plan and accurately deliver spinal SBRT treatments.

1. Introduction
Stereotactic body radiation therapy (SBRT) is used to treat some patients suffering from spinal metastases [1, 2]. Spine SBRT plans exhibit very steep dose gradients in order to spare the spinal cord while delivering sufficient dose to the target volume, which is comprised of the vertebral body and often partially wraps around the cord. Our clinic has recently begun development of a spinal SBRT program. To assist in protocol development and validation, we created an anthropomorphic spine phantom that enables the use of planar dosimeters to measure dose in the target and critical structures. In this report we present the phantom design and results of our initial spine SBRT tests. The purpose of this work is to 1) validate the image guidance technique for the treatment site, and 2) investigate the accuracy of dose calculation within high-density inhomogeneities using our clinical treatment planning system. Because our aim was to measure dose within a high density object, gel dosimeters were not readily applicable to this experiment.
2. Methods

2.1. Anthropomorphic spine phantom

A segment of the thoracic spine (7 vertebrae, approximately 17 cm long) of a previously-treated lung cancer patient was contoured and exported to a 3D triangulated mesh. The mesh was processed for 3D printing using Slic3r software (Slic3r Prusa Edition) to export G-code 3D printer instructions for a fused deposition modelling 3D printer (Prusa i3 MK3, Prusa Research). Printing was performed (100% infill) with an iron-doped polylactic acid (PLA) filament (3D Printing Canada), resulting in a mean CT number of approximately 750 HU and a relative electron density of approximately 1.4 [3]. Thus, the printed spine appears similar to bone on CT / CBCT imaging, allowing us to test the accuracy of our clinical image guidance techniques for patient setup. For this study, the spine was printed in two halves, cut along the sagittal plane, creating a slot for the insertion of a single piece of film (Figure 1a). Metal BBs were embedded in the flat face of the film slot to facilitate registration of dose distributions in analysis.

The printed spine was then placed within a body-shaped water phantom (Modus QA), held in place by a custom made plastic mount made from polycaprolactone (PCL). The mount was made by heating the PCL (Polydoh, Materialix Inc.) to 60 °C, at which point it becomes easily mouldable. The spine phantom was pressed into the PCL, creating a unique imprint for reproducible positioning. This mount was attached to a 0.5 cm thick sheet of Superflab using double-sided tape. This assembly was similarly affixed to the bottom of the water tank. Figure 1b shows the complete, water-filled phantom.

![Figure 1. a) Halves of the 3D printed spine. Embedded metal BBs used for film registration are indicated by the red arrows. b) Assembled phantom filled with water. c) Axial slice of planning CT scan of the phantom, with contoured target/OAR volumes transferred from corresponding patient CT.](image)

2.2. Treatment planning and delivery

2.2.1. Volume contouring

Realistic GTV, CTV, PTV volumes, as well as spinal cord and esophagus OARs, were contoured by a radiation oncologist on the original patient anatomy. A spinal cord PRV was generated using a 2 mm expansion on the spinal cord. For optimization and prescription purposes, a modified PTV was created by cropping the PTV out of the esophagus and cord PRV volumes. Subsequently, the contours were transferred to a planning CT scan of the phantom (Figure 1c) by rigidly registering the patient CT image to the phantom image (based on the spine).

2.2.2. Plan optimization and dose calculation

The treatment was initially planned to deliver a prescribed dose of 27 Gy in 3 fractions, normalized such that V100% = 90% for the modified PTV (volume = 20.5 cc). Additionally, the plan was optimized such that the maximum point dose within the PTV was less than 130% of the prescription, and that V100% ≥ 99% for the GTV. For OARs, the dose tolerances were D0.1cc < 24 Gy for the cord PRV, D0.1cc < 22 Gy for the spinal cord proper, and D0.1cc < 27 Gy for the esophagus (additionally, D0.35cc < 20 Gy).
The treatment was planned using both a flattened 6 MV beam as well as a flattening filter free 10 MV beam (10FFF). Two coplanar full arcs (collimator 30º and 330º) were used.

The dose distribution was calculated using the convolution-based Analytical Anisotropic Algorithm (AAA) and the Acuros XB algorithm, a grid-based Boltzmann equation solver (v13.6, Varian), both with a 2 mm resolution calculation grid. Since the film dosimeter is near water equivalent, dose-to-water was determined to be the appropriate dose reporting method when comparing Acuros calculations to film measurements.

2.2.3. Treatment delivery
For each delivery, the spine phantom was assembled with a piece of radiochromic film (Gafchromic EBT3, International Specialty Products, Inc) inserted and held in place with tape. Films were marked with permanent marker at the location of each metal BB, for registration of dose distributions. The prescription dose was scaled down such that the maximum dose was approximately 3 Gy, to account for the dynamic range of the readout system. Treatment was delivered using a Varian Truebeam linear accelerator equipped with a 6 degree of freedom couch for pitch and roll corrections. The phantom was set up using laser alignment marks followed by cone beam CT with a bony match on the spine for shift and rotational corrections. Image matching was performed by radiation therapists, simulating the clinical process.

2.3. Dosimetry

2.3.1. Film readout and calibration
In this study, Gafchromic EBT3 film dosimeters were used. Films were imaged using an in-house point scanner, which operates in a raster-scan fashion to acquire images at 0.6 mm spatial resolution with very low stray light contamination [3]. Measured optical densities were converted to dose using a calibration curve obtained from a series of well characterized 10 x 10 cm² field irradiations (depth = 2 cm) to films from the same batch (8 dose levels between 0-4 Gy). Phantom film measurements were corrected for variation in machine output and CBCT imaging dose (approximately 2 cGy).

2.3.2. Dosimetric analysis
Analysis was performed using the Film Dosimetry Slicelet within the 3DSlicer software [4, 5] (www.slicer.org). The plane of the calculated dose distributions corresponding to the film dosimeter was extracted, aided by the fiducial markers in the phantom. This plane was aligned with the measured film using the optical fiducials corresponding to the BBs. Dose profiles were taken along the steep gradient at the mid-height of the target volume in the ANT-POST (AP) direction, as well as through the target in the SUP-INF (SI) direction, for qualitative comparison. Additionally, 2D gamma dose comparisons were performed within the film sheet, using a 3%/1mm criteria (5% dose cutoff). The tight distance criterion reflects the importance of geometric accuracy when treating targets adjacent to the spinal canal.

3. Results and Discussion
Figure 2a shows a zoomed axial view of the 6 MV calculated dose distribution (AAA). The sagittal slice corresponding to the film plane is shown in Figure 2b. Figure 2c-f shows dose profiles along the lines indicated in Figure 2b. Table 1 contains the gamma passing rates (3%/1mm, 5% cutoff, evaluated within the film sheet) for the comparison of calculated and measured doses for the 6 MV and 10FFF plans. Our results are discussed from the standpoint of both dosimetric and geometric accuracy in the next sections.
Table 1. Gamma pass rates for measured vs. planning system doses.

| Plan            | 2D Gamma Pass Rate (3%/1mm) |
|-----------------|-----------------------------|
| 6 MV AAA        | 85.4%                       |
| 6 MV Acuros     | 92.1%                       |
| 10FFF AAA       | 78.6%                       |
| 10FFF Acuros    | 90.1%                       |

Figure 2. a) Zoomed-in axial view of the 6 MV treatment plan (AAA dose calculation), demonstrating cord sparing. Colourwash ranges from 90% of prescription to the maximum dose in the plan (122.8%). Note that the film slot can be seen on the CT image. b) Zoomed-in sagittal view of planning CT, with registered film dose image overlaid. c-f) Calculated and measured dose profiles along the lines specified in (b) for the 6 MV plan (c,d) and 10FFF plan (e,f). Note the scaling difference in the horizontal axes of the AP and SI profile plots.
3.1. Dosimetric accuracy
Examining the dose profiles in Figure 2, we clearly see that the AAA-calculated dose does not agree well with the film measurement in the high-dose region (inside the bone substitute), underestimating dose by approximately 5-7%. This is reflected in the 2D gamma comparison results (figure not shown), wherein the majority of failures lie within the target and not near the dose gradients. Meanwhile, the Acuros calculation shows very strong agreement within the high dose region. In our experiment, the film measurements correspond to a dose-to-water in “bone”, while AAA reports a dose to scaled water. With Acuros, dose-to-water in medium (i.e. the dose to a small water voxel surrounded by the medium) was calculated. Therefore, it is not surprising to see much better agreement with Acuros than with AAA when using film dosimeters sandwiched in a high density object. Our discrepancy between dose-to-water (Acuros / measurement) and dose to scaled water (AAA) is consistent with the results of previous Monte Carlo simulation work by other groups [6].

3.2. Geometric accuracy
With the discussion of dosimetric accuracy in mind, we can compare the film measurements and Acuros dose calculations to evaluate the geometric accuracy of our delivery. Offline examination of CBCT-CT registrations performed by therapists showed very good alignment of the spine (Figure not shown). From the profiles (Figure 2), we see that the steep dose gradients in the SUP-INF and ANT-POST directions are very well aligned, indicating a high degree of accuracy in setup and registration along those directions. For both 6 MV and 10FFF deliveries, the location of the 50% isodose line of the steep dose gradients is within 0.5 mm in the ANT-POST direction and within 0.9 mm in the SUP-INF direction. These distances lie within tolerance for machine treatment/imaging isocentre.

2D gamma comparisons for Acuros vs. film showed pass rates above 90% for both 6 MV and 10FFF plans at 3%/1mm criteria. Considering the strict distance threshold, for a 2D comparison (less forgiving than 3D) this result is reasonable, especially given the agreement seen in dose profiles. Overall, our results indicate that we are able to achieve sufficient geometric accuracy for linac-based spine SBRT treatments.

4. Conclusion
In this study, we demonstrated the use of an anthropomorphic spine phantom for the validation of a spinal stereotactic body radiation therapy treatment protocol. We achieved very good agreement between film measurement and dose calculations performed using the Acuros XB algorithm (dose-to-water) in the high-density bone substitute. Geometrically, we observed very good alignment of the sharp dose gradients in the SUP-INF and ANT-POST directions, which gives us confidence in our image guidance technique. Our results are a strong indicator of our ability to plan and accurately deliver spinal SBRT treatments. The key limitation of our work was the lack of real patient motion, and correspondingly the inability to test immobilization techniques. Also, our initial work only utilized 2D dosimetry in a single plane. Future work will extend to 3D through the use of multiple film planes, which will allow a more complete validation of geometric accuracy.

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6. References
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