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Prototype modulated orthovoltage stereotactic radiosurgery cones

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ABSTRACT

This work sought create a set of prototype modulated orthovoltage stereotactic radiosurgery (SRS) cones, and to perform a dosimetric characterization of the prototypes. Four radiosurgical cone collimators (with cone diameters of 5 mm, 6 mm, 8 mm, and 10 mm) were built for use with an orthovoltage unit, along with epoxy-infiltrated bonded tungsten filters designed to shape the resulting dose distributions. Dosimetry measurements were performed using radiochromic film in a water phantom for both filtered and unfiltered cones at depths of 2.5 cm, 5.0 cm, and 7.5 cm. Films were scanned using a flatbed scanner and the beam profiles were analyzed. Extracted beam profiles validated the ability to optimize dosimetric results based on desired dose distributions, where for this work the goal distributions were rectangular functions. Radiochromic film measurements of dose distributions in water confirmed that the prototypes were able to achieve distributions approaching rectangular functions at depth, as determined by penumbra and flatness statistics. A prototype set of novel, modulated orthovoltage SRS filtered cones was successfully constructed, and a full dosimetric characterization was completed in water. In all configurations, filtered, optimized cones were able to achieve distributions more closely approaching the goal distributions compared to open cones.

1. Introduction

This project focuses on the creation of a homogeneous dose distribution conforming strictly to a target volume, with steep dose gradients outside the target—an overall distribution similar in shape to a rectangular function (or a “top hat”) in stereotactic radiosurgery (SRS). Such distributions may be desirable for some SRS targets, such as those with functional tissue included within the target volume, and may be of interest for small animal irradiations (Chang et al., 2005; Massager et al., 2006; van Eck and Horstmann, 2005). The use of orthovoltage energies for the treatment of sites that are traditionally irradiated using conventional high-energy linear accelerators has been detailed in the literature (Bazalova-Carter et al., 2017; Breitkreutz et al., 2017; Garnica-Garza, 2016; Prionas et al., 2012; Zeinali-Rafsanjani et al., 2017). Previously published studies have also described using orthovoltage energies for SRS and stereotactic body radiation therapy (SBRT) procedures (Deloar et al., 2004, 2006; Fagerstrom et al., 2016; Hanlon et al., 2009; Keller et al., 2007; Keller et al., 2009; O'Malley et al., 2006; Sánchez-Arreola and Garnica-Garza, 2017).

Previous computational work (Fagerstrom et al., 2017) designed variable-thickness tungsten filters fitted into orthovoltage stereotactic cone collimators using inverse planning optimization techniques. These optimization techniques included a Genetic Algorithm search heuristic to determine optimal filter geometry based on desired dose distributions. In this case, the goal distributions were rectangular function dose distributions at depth. Using the geometry determined by the optimization process, Monte Carlo simulations were used to verify the dose distributions at various depths with the optimized filter and cone assemblies and compare these distributions to those derived from open cone collimators. In the current work, prototypes of those assemblies were constructed, along with a custom support and positioning framework, and the dosimetry of the prototypes was characterized using radiochromic film measurements in water.

2. Methods and materials

2.1. UWMRRC orthovoltage unit

The University of Wisconsin Medical Radiation Research Center (UWMRRC) maintains a constant potential kilovoltage x-ray system using a Kimtron (Oxford, CT) Polaris 360 generator and a Comet (Flamatt, Switzerland) 320 tungsten anode tube with a 5.5 mm nominal focal spot size. The x-ray beam used in this work, denoted UW250-M, is a moderately filtered, 250 kVp beam with a first half-value layer of

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18.3 mm aluminum (or 3.01 mm copper), a homogeneity coefficient of 98, and an effective energy of 145 keV (Nunn et al., 2008). Its spectrum has been thoroughly characterized using Monte Carlo simulations and measurements with a low-energy germanium detector (Moga, 2011; Moga and DeWerd, 2010). Previous work at the UWMRRC included the design and construction of a custom thin-window water phantom for use with the orthovoltage unit (Lawless, 2016). This phantom accommodates a fixed horizontal beamline irradiation geometry, with a 0.146 cm-thick, 18 cm-diameter polymethyl methacrylate (PMMA) window included to minimize perturbation of the orthovoltage beam.

2.2. Cone collimator, filter, and positioning chassis construction

Cone and filter assemblies were constructed for use with the UWMRRC orthovoltage unit. Work by Fagerstrom et al. (2017) used inverse planning techniques to design filtered stereotactic cone collimators. These geometries were modeled in Monte Carlo simulations to validate the resulting dose distributions. Simulations were performed for depths of 2.5 cm, 5.0 cm, and 7.5 cm, with cone sizes of 5 mm, 6 mm, 8 mm, and 10 mm. Based on the designs described in the previous work, the outside rapid prototyping firm RP + M (Avon Lake, Ohio) was commissioned to manufacture the prototype filters using a binderjetting printer with the capability of 3D printing epoxy-infiltrated tungsten parts. Although the exact composition of the filters was not available from the manufacturer, an independent analysis (ALS Global Life, Tuscon, AZ) of the filter material indicated a density of 11.206 g/cm^3, with a composition, by weight, of 4.08% organic material and 95.92% tungsten. This was the composition used in the Monte Carlo modeling design process (Fagerstrom et al., 2017). A photograph of the filter prototypes is shown in Fig. 1.

Four $(9 \times 10 \times 3.175)$ cm^3 nondivergent cone collimators for use with the UWMRRC orthovoltage unit were constructed using high-leaded machining brass (Alloy 353). Transmission of the UW250-M beam through the solid brass was measured to be 0.12 %± 0.02% using a 15 cm^3 active volume parallel plate chamber by finding the ratio of raw charge readings of the chamber in air at 100 cm from the source, with and without the solid brass present. Apertures were milled into the collimators with precision reamers for cone diameters of 3 mm, 4 mm, 5 mm, and 6 mm, which, when projected to the plane of measurement, resulted in beam profiles of nominal widths 5 mm, 6 mm, 8 mm, and 10 mm. For simplicity, cones are henceforth designated by their nominal beam profile width at the plane of measurement. Dowel pins were used to position filters temporarily on the collimator plane distal from the source, and three set screws fixed each filter flush against the collimator surface. Filters could be removed for open cone measurements.

Fig. 1. A photograph of the binderjetted epoxy-infiltrated bonded tungsten filter prototypes: 5 mm cone filter (upper left), 6 mm cone filter (upper right), 8 mm cone filter (lower left), and 10 mm cone filter (lower right).

Photographs of the cone collimators are shown in Fig. 2.

A mobile frame chassis was constructed, along with a variable-position ceiling alignment laser system, for positioning the collimator and filters along the central beam axis of the UWMRRC orthovoltage unit. The chassis consisted of an aluminum extrusion framing base that was temporarily affixed to the UWMRRC orthovoltage tube stand housing, along with two precision stages: one with tip, tilt, and rotational adjustment, and one with three linear axes cross-roller adjustment, allowing for fine-tuning of collimator position with six degrees of freedom. A photograph of the frame chassis affixed to the UWMRRC orthovoltage tube stand housing is shown in Fig. 3.

A green diode laser (45° fan angle, 532 nm, 4.5 mW fixed-focus) was acquired to construct a translational ceiling laser system for positioning the collimators. The laser was factory focused to a distance of 1219 mm, which corresponds to the approximate distance between the beam path and the laser's mounted position. The laser was mounted on a rail-track system that allows for precision positioning using custom software designed in LabVIEW (National Instruments Corporation, Austin, TX). Photographs of the laser positioning system are shown in Fig. 4.

Room lasers fixed to the known beam axis, as well as the variable position ceiling laser, were used for establishing all irradiation geometry. The frame chassis was used to position the collimator 62.5 cm from the focal spot (measured from the collimator plane farthest from the source) as determined by the variable-position ceiling laser. The chassis was locked in place on the orthovoltage stand housing based on approximate alignment markings on the aluminum extrusion frame. Coarse adjustment was achieved by adjusting longitudinal, lateral, and vertical position of the chassis arms, as well as shimming the chassis itself (if necessary). The collimator was then leveled using a precision digital level and fine adjustments were made with the precision stages. Lastly, further fine adjustments were achieved using the precision stages to match the collimator surface with the variable-position ceiling laser.

Similarly, the thin-window water phantom was aligned using the ceiling laser. The tank was mounted on an aluminum extrusion frame with four adjustable feet, allowing the tank to be leveled to assure the beam entered the phantom perpendicularly to the window surface. Once level, the tank was positioned based on the ceiling laser to achieve the desired depth.

2.3. Radiochromic film handling

Dosimetric characterization of the prototype cones was performed using the most recent iteration of EBT3 radiochromic film (Ashland Specialty Ingredients, Bridgewater, NJ) from a single batch (Lot 11051301). Film handling methods were followed as described by the recommendations of the American Association of Physicists in Medicine (AAPM) Radiation Therapy Task Group 55 (Niroomand-Rad et al., 1998). Storage and irradiation conditions followed manufacturer recommendations. Films were cut into segments at least 48 h prior to initial scanning. To ensure consistent alignment of films, segments were immediately marked with numbered fiducials after cutting using a fine-tipped permanent marker to record orientation and side of the segment with respect to the original sheet. Samples were cut from randomized positions on film sheets in an effort to reduce effects of film non-uniformity (Reinhardt et al., 2012). To avoid humidity and water penetration effects during in-water measurements, all film samples were placed within vacuum-sealed, air-tight Foodsaver® (Sunbeam Products, Inc., Boca Raton, FL) packets, as described by Rosen (2015), Soares (2009), and Massillon et al. (2013). Film segments cut for calibration irradiation and placed in packets are pictured in Fig. 5.

Film scanning was completed with an EPSON Expression® 10000XL white-light flatbed document scanner, S/N 026388 (Epson America, Long Beach, CA) and its associated software, EPSON Scan v.2.20A. All images were acquired in transmission mode and landscape orientation with the film elevated from the glass and positioned in the center of the