

Development and characterization of a three-dimensional film stack dosimeter

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Abstract. A three-dimensional (3D) film stack dosimeter (FSD) using Gafchromic[®] EBT2 film was characterized for use in external-beam radiotherapy. The FSD was found to have negligible energy dependence and orientation dependence less than 2% using Monte Carlo simulations. Percent-depth-dose measurements with the FSD aligned parallel and perpendicular to the beam axis agreed with Monte Carlo simulations within 2%. Measurements of a ⁶⁰Co slit field with the FSD and thermoluminescent dosimeters agreed with a gamma passing rate of 97.6% using 1.5%/1.5 mm criteria. Edge artifacts were smaller than 2 mm, minimally affecting the usable measurement volume. The FSD is water equivalent, energy independent and orientation independent within measurement uncertainty at ⁶⁰Co energies, providing a 3D dosimeter that can be analyzed with a desktop scanner.

1. Introduction

Advancements in conformal radiation therapy procedures have increased the need for three-dimensional (3D) dosimeters to verify dose calculation algorithms and treatment deliveries. Fricke gel and polymer gel dosimeters have been extensively investigated and have shown promise as 3D dosimeters [1-4]. However, the accuracy of Fricke gel dosimeters is limited by post-exposure diffusion [5-7], and the response of polymer gel dosimeters depends on the free-oxygen concentration during preparation [8]. Additionally, these dosimeters require specialized readout techniques, such as magnetic resonance imaging or optical computed tomography, and are subject to edge artifacts [9]. The development of a stable, easy-to-analyze 3D dosimeter is essential and could result in broader clinical implementation of 3D dosimetry. The purpose of this work was to develop and characterize a 3D radiochromic film stack dosimeter (FSD) that could be read out with a standard desktop scanner for use in external-beam radiotherapy. The energy dependence, orientation dependence and water equivalence of the FSD were investigated.

2. Materials and methods

2.1. Phantom design

Gafchromic[®] EBT2 film (International Specialty Products, Wayne, NJ) was used in this work. A phantom housing to maintain alignment of the films was fabricated out of Virtual Water[™] (VW) (Med-Cal, Verona, WI). The phantom (figure 1) is a truncated sphere with a central cavity that holds 22 circular films, 3.8 cm in diameter, with a radial clearance of 60 μ m. The films are separated by 1 mm thick VW spacers for a total stack height of 2.7 cm. Two semicircular tabs on the outer diameter of each film fix the azimuthal orientation of the stack. A cylindrical phantom housing (CPH) with a



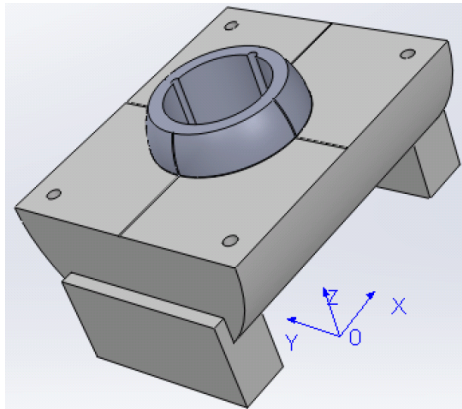


Figure 1: Cutaway schematic of the film stack dosimeter (FSD) phantom housing within the cylindrical phantom housing (CPH).

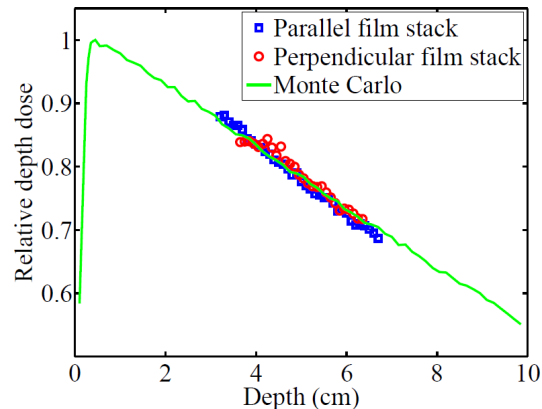


Figure 2: Percent-depth-dose profiles in a cylindrical water phantom simulated with MCNP5 and measured with the film stack dosimeter (FSD).

10 cm diameter and 12 cm length was also fabricated from VW. The CPH has a central cavity to accommodate interchangeable phantoms that house the FSD, thermoluminescent dosimeters (TLDs) and an Exradin A1SL ionization chamber (Standard Imaging, Middleton, WI), the latter two of which can be used to verify dose measurements made with the FSD.

2.2. Monte Carlo simulations

The response of EBT2 film to ionizing radiation is dependent on both the energy [10] and the relative orientation [11] of the incident radiation. The potential impact of these dependencies was explored with Monte Carlo (MC) simulations using MCNP5 v1.60. For all simulations and measurements, the coordinate axes were defined as shown in figure 1, with the beam axis parallel to the y axis. The simulations used a collimated photon point source with a ^{60}Co teletherapy spectrum.

The energy dependence was investigated by simulating the energy spectrum of the photon fluence through the film in the calibration and FSD geometries. The calibration geometry consisted of a $(3 \times 3) \text{ cm}^2$ piece of EBT2 film between two 5 cm thick VW slabs. The FSD was modeled at the center of the CPH with air gaps of 25 μm between films and VW spacers. An energy-binned cell flux tally, with bin widths of 25 keV, was used to determine the energy spectrum of the photon fluence through the calibration film and the top, middle and bottom films of the FSD. The orientation dependence of the FSD response was determined using an energy deposition tally to simulate the dose to a cylindrical volume parallel to the x axis in the central film. Simulations were completed with the source rotated about the central axis of the tally volume in 10° increments. The orientation dependence of film dosimeters is affected by the presence of air gaps around the film [11], so air gaps between films and spacers of 0, 25, 50 and 100 μm were considered.

The central-axis percent-depth-dose (PDD) profile in a water phantom from a $(10 \times 10) \text{ cm}^2$ ^{60}Co field at a source-to-axis distance (SAD) of 100 cm was simulated to compare the attenuation of the FSD with that of water. The size and orientation of the water phantom matched that of the CPH. The dose was tallied to cylindrical volumes at depth along the beam axis with radii of 0.5 mm and thicknesses of 0.1 mm. The tally volumes were spaced at intervals of 1.5 mm, decreasing to 0.5 mm near the depth of maximum dose.

2.3. Experimental verification

For experimental verification of the FSD, all exposures were performed with the University of Wisconsin Accredited Dosimetry Calibration Laboratory (UWADCL) Theratron 1000 ^{60}Co irradiator (Theratronics, Ontario, Canada). The UWADCL maintains a secondary absorbed dose-to-water standard, so use of the ^{60}Co irradiator reduced the uncertainty of the dose measurements used to characterize the FSD. The PDD profile of a $(10 \times 10) \text{ cm}^2$ field at a SAD of 100 cm was measured with

the FSD oriented perpendicular and parallel to the beam axis for comparison with the orientation dependence simulations. The dose at a 5.6 cm depth in the CPH was measured using an A1SL ionization chamber to convert the MC-simulated PDD profile, normalized per source particle, to dose for comparison with the FSD measurements. The FSD was also used to measure the dose distribution from a 12 mm-wide slit field for comparison with a TLD phantom measurement. A slit collimator comprised of two 10 cm thick lead bricks was used. For each exposure, the respective dosimeter and phantom housing were placed within the CPH to ensure reproducible positioning.

2.3.1. Film calibration and analysis

The film response was calibrated and analyzed using the net optical density method described by McCaw *et al.* [12]. Sets of six (3x3) cm² pieces of EBT2 film were exposed to calibration doses of 0, 24.8, 36.6, 52.6, 76.2, 111, 160, 232, 337 and 489 cGy. Control films were used to account for background. All films were scanned individually in portrait orientation immediately prior to and one week after exposure using an Epson® Expression® 10000XL flatbed scanner (Epson America, Long Beach, CA) set to professional mode, 48-bit color and 72 dpi. The films were centered on the scan bed and lifted off of the glass surface using saturated radiographic films as masks. The film images were analyzed using MATLAB® (MathWorks, Natick, MA). Positioning of the films on the scan bed was confirmed to be reproducible within 1 pixel, so the films were compiled and registered without additional transformation to generate a 3D dose distribution.

2.3.2. TLD analysis.

LiF:Mg,Ti TLDs [Harshaw TLD-100 microcubes (Thermo Electron Corporation, Oakwood Village, OH)] were used to verify the FSD measurement of the ⁶⁰Co slit field. The TLD phantom holds 125 (1x1x1) mm³ microcubes arranged in five crosses in each of five different slices parallel to the *x-z* plane. TLDs were annealed using the Cameron procedure [13] and stored for at least 24 h prior to exposure. The TLDs were read out with a Harshaw 5500 TLD automatic reader at least 24 h after exposure. The raw readings were corrected for background and non-linearity of the photomultiplier tube. Three sets of five TLDs were exposed to calibration doses of 5.00, 125 and 250 cGy. A linear fit was applied to the dose as a function of thermoluminescence.

3. Results

For energies below 500 keV, where the energy response of EBT2 film is greatest [10], the maximum difference in the simulated photon energy spectra for the calibration and FSD geometries was less than 0.5%. Overall, the greatest difference in the spectra for the two geometries was 1.4% at 1.175 MeV, where the energy response of EBT2 film is minimal [10]. For incident beam angles of 0° to 80° relative to the axis normal to the film plane, only the response in the 100 µm air gap geometry varied more than ±1%. For the parallel FSD geometry (i.e., 90° angle of incidence), the under-responses relative to the 0° orientation for air gaps of 0, 25, 50 and 100 µm were 0.9%, 1.4%, 1.7% and 2.5%, respectively. The air gaps in the FSD were measured to be approximately 20 µm. All simulations had an expanded (*k* = 2) Type A uncertainty of ±1%.

Because the PDD measurements with the FSD did not extend to the depth of maximum dose, the measurements were normalized to the maximum dose determined from the simulated PDD profile and the ionization chamber measurement. The measured and simulated PDD profiles are shown in figure 2. The FSD measurements agreed with the ionization chamber measurement within 1%. The depth dose values measured by the FSD in the perpendicular and parallel geometries agreed within 2%, verifying the results of the orientation-dependence simulations. Furthermore, the measured and simulated PDD profiles agreed within 2%, indicating the water equivalence of the FSD.

Select dose profiles at a depth of 4.1 cm in the CPH from FSD and TLD measurements of the ⁶⁰Co slit field are shown in figure 3. The dashed lines and error bars indicate the expanded (*k* = 2) overall uncertainty of the FSD (4.5%) and TLD (7.8%) measurements, respectively. The FSD and TLD data agreed within the measurement uncertainty. Additionally, the two dose distributions agreed with a

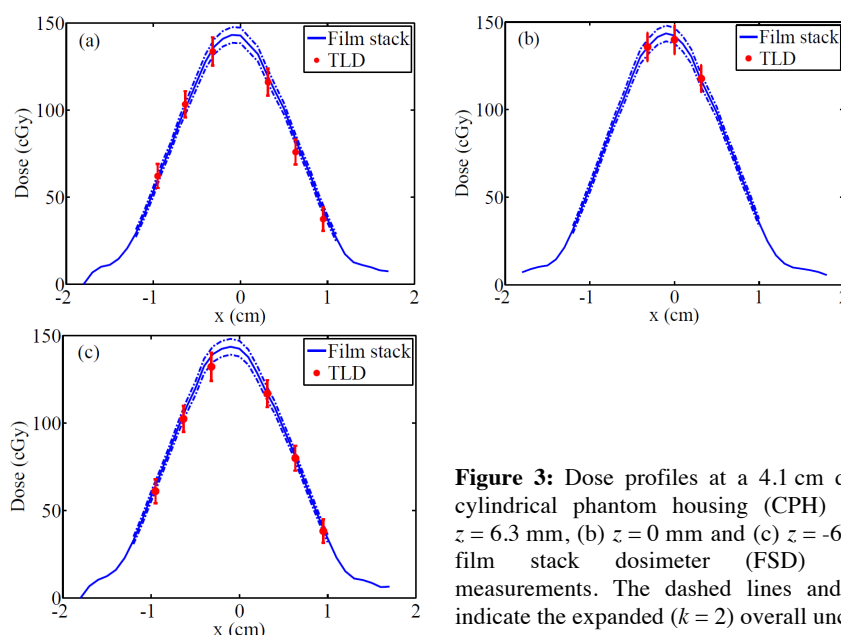


Figure 3: Dose profiles at a 4.1 cm depth in the cylindrical phantom housing (CPH) through (a) $z = 6.3$ mm, (b) $z = 0$ mm and (c) $z = -6.3$ mm from film stack dosimeter (FSD) and TLD measurements. The dashed lines and error bars indicate the expanded ($k = 2$) overall uncertainty.

gamma passing rate of 97.6% using 1.5%/1.5 mm criteria. Edge artifacts from the FSD measurements encroached less than 2 mm, permitting the use of smaller 3D detectors without loss of information.

4. Conclusions

A FSD using EBT2 film was developed and characterized. Within measurement uncertainty the FSD is water equivalent, energy independent and orientation independent at ^{60}Co energies. The measurement volume of the FSD is minimally affected by edge artifacts. Agreement with TLD and ionization chamber measurements verifies the accuracy of the FSD and analysis with a desktop scanner. The FSD is shown to be a valid 3D dosimeter for external-beam radiotherapy measurements. Future work will extend this investigation to higher-energy photon beams.

5. Acknowledgments

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6. References

- [1] Kelly R G *et al* 1998 *Med. Phys.* **25** 1741-50
- [2] Maryanski M J *et al* 1996 *Med. Phys.* **23** 699-705
- [3] Baldock C *et al* 2010 *Phys. Med. Biol.* **55** R1-63
- [4] Baldock C *et al* 1998 *Phys. Med. Biol.* **43** 695-702
- [5] Pedersen T V *et al* 1997 *Phys. Med. Biol.* **42** 1575-85
- [6] Harris P J *et al* 1996 *Phys. Med. Biol.* **41** 1745-1753
- [7] Baldock C *et al* *Australas. Phys. Eng. Sci. Med.* **24** 19-30
- [8] Maryanski M J *et al* 1994 *Phys. Med. Biol.* **39** 1437-55
- [9] Oldham M and Kim L 2004 *Med. Phys.* **31** 1093-104
- [10] Sutherland J G H and Rogers D W O 2010 *Med. Phys.* **37** 1110-6
- [11] Suchowerska N *et al* 2001 *Phys. Med. Biol.* **46** 1391-7
- [12] McCaw T J *et al* 2011 *Med. Phys.* **38** 5771-7
- [13] Cameron J R *et al* 1964 *Health Phys.* **10** 25-9