J Radioanal Nucl Chem (2016) 307:2505–2508
DOI 10.1007/s10967-015-4563-x

Measuring the photon depth dose distribution produced by a medical linear accelerator in a water-equivalent radio-fluorogenic gel

Peter A. Sandwall[1] · Henry B. Spitz[2] · Howard R. Elson[3] · Michael A. S. Lamba[3] · William B. Connick[4] · Henry Fenichel[5]

Received: 28 June 2015 / Published online: 26 October 2015

Abstract The present work describes use of a water-equivalent radio-fluorogenic gel dosimeter for measurement of a depth dose distribution from a medical linear accelerator. Relative depth dose distributions for a 6 MV photon beam were measured with a novel radio-fluorogenic gel comprised of aqueous gelatin and coumarin-3-carboxylic acid. Agreement was within 3 % of published values in most areas of electronic equilibrium. Results support continued development of radio-fluorogenic gel dosimetry systems for quality assurance of clinical photon beams.

Keywords Radiation dosimetry · Radio-fluorogenic gel · Gel dosimetry · Luminescent dosimetry

✉ Peter A. Sandwall
pasandwall@gmail.com

[1] Radiation Therapy, Vantage Oncology LLC, 10550 Montgomery Road Suite #14, Cincinnati, OH 45242, USA

[2] Mechanical and Materials Engineering, College of Engineering and Applied Science, University of Cincinnati, 2901 Woodside Drive, Cincinnati, OH 45221, USA

[3] Department of Radiation Oncology, College of Medicine, University of Cincinnati, 234 Goodman Street, Cincinnati, OH 45267, USA

[4] Department of Chemistry, McMicken College of Arts and Sciences, University of Cincinnati, 7148 Edwards One, Cincinnati, OH 45221, USA

[5] Department of Physics, McMicken College of Arts and Sciences, University of Cincinnati, 7148 Edwards One, Cincinnati, OH 45221, USA

Introduction

The ability to measure distributions of absorbed dose with high spatial resolution has been an ongoing pursuit in the field of radiation dosimetry. With near tissue equivalence, various types of gel dosimeters have been investigated as the ideal sensor system [1–5]. Fluorescent detection techniques are particularly promising due to their ability to form high-resolution images.

Aqueous coumarin-3-carboxylic acid (C3CA) has been reported as a fluorescent chemical dosimeter for radiotherapy with favorable characteristics including reproducibility, stability, and linear dose response [6]. Development and application of C3CA as a chemical dosimeter continues to be an active area of research [7, 8]. The present study details initial investigations of a novel gelatin based solution of C3CA as a water-equivalent radio-fluorogenic gel dosimeter for application to quality assurance measurements.

Theory

Radio-fluorogenic detectors rely on the production of fluorescent products formed in response to ionizing radiation. In water, energy deposition by ionizing radiation results in radiolysis producing hydroxyl free radicals. Aromatic compounds in aqueous solution may undergo hydroxylation to form fluorescent products.

C3CA reacting with hydroxyl radicals generated by water radiolysis, yield the fluorescent product 7-hydroxy-coumarin-3-carboxylic acid (7HO-C3CA). 7HO-C3CA is a derivative of umbelliferone, a well characterized fluorescent probe with UV excitation maxima at 365 nm. Fluorescent 7HO-C3CA is produced by a substitution reaction between C3CA and hydroxyl radicals (Fig. 1).

Experimental

Samples of 1 mM coumarin-3-carboxylic acid in 7 % by weight gelatin were prepared with filtered and deionized water obtained from EASYpure water purification system (Barnstead International). All reagents were obtained from Fisher Scientific (Baltimore, MD); 98 % C3CA ($C_{10}H_6O_4$) (Acros Organics, Baltimore, MD) and food grade, porcine type A gelatin (bloom strength $\sim$ 260, pH $\sim$ 5, and viscosity $\sim$ 40). To prevent microbial growth, samples were stored at low temperature (5 °C) except during irradiation and analysis.

Experimental, fabrication

To permit effective dispersion, 7 % gelatin was allowed to 'wet', during which gelatin was placed in a beaker and soaked with half the total volume of cold distilled water for 15–30 min. In a separate beaker, 1 mM C3CA was brought into solution by bringing a fraction of the total volume of water to a boil. After the gelatin was been 'wet', the fluor solution was added with the remaining fraction of water. Temperature of the gel solution was raised to 35 °C and maintained for approximately 90 min, with care taken not to exceed 40 °C which may denature the gelatin. When the gel was optically clear and free of visible colloidal structures, the solution was removed from heat and pipetted into polymethyl-methacrylate cuvettes. Gels were left to cool overnight at ambient temperature.

Experimental, irradiation

Irradiations were conducted with a medical linear accelerator (Varian Medical Systems; Pal Alto, CA) providing a nominal photon energy of 6 MV. Cuvettes were arranged as generalized voxels, a free standing stack of 4 rows and 10 columns, on the treatment couch. Cuvettes were placed with the top surface at 100 cm source to detector distance and irradiated with a square 10 cm field.

Experimental, analysis

Fluorescent analysis was performed with a Cary Eclipse (Varian, Inc.; Pal Alto, California) fluorescence spectrophotometer equipped with a Xe flash-bulb and fixed right-angle collection. Data acquisition was optimized using both excitation and emission scans of samples. Excitation and emission slit widths were set to 5 nm. Response was defined as the normalized fluorescent intensity at 445 nm.

Results and discussion

Water equivalence

The atomic number (Z) is recognized as the principle characteristic for comparing photon interaction coefficients in various materials. This led to development and use of "effective Z" as a measure of a radiologic equivalency. Computed linearly by weighted addition, a material is termed "equivalent" if it possesses the same effective Z. The elemental composition (Table 1) and chemical formulation (Table 2) are shown for the radio-flourogenic gel evaluated in this study.

The effective Z of the radio-fluorogenic gel deviated 0.04 % from water, less than the difference between water to tissue. The gels differed from tissue 2.24 %, similar to the 2.19 % deviation of water from ICRU 44 soft tissue [9]. These results demonstrate water-equivalence and support suitability of the gel as a tissue substitute.

Photon depth dose

Depth dose data has been shown to be an accurate method for self-calibration and assessment of dosimeter response [10]. Dose response was determined by applying vendor

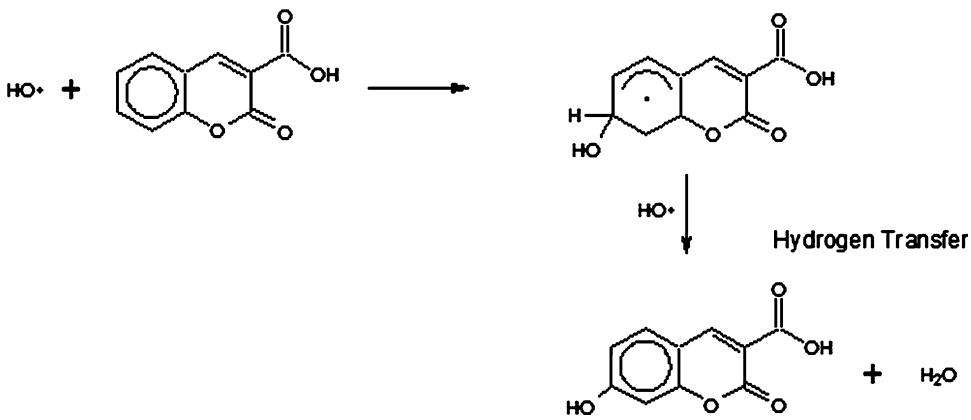

Fig. 1 Illustration of coumarin-3-carboxylic acid undergoing hydrogen abstraction and substitution with hydroxyl radicals, yielding fluorescent product 7HO-C3CA, with excitation maximum in 365 nm

Table 1 Elemental composition of detector constituents and ICRU 44 soft tissue with effective Z and percent deviation from water and tissue [9]

Element	Z	A	Water	Soft tissue	Gelatin	C3CA	7HO-C3CA
Hydrogen	1	1	0.111	0.102	0.108	0.032	0.029
Carbon	6	12	–	0.143	0.020	0.632	0.583
Nitrogen	7	14	–	0.034	0.007	–	–
Oxygen	8	16	0.889	0.708	0.858	0.336	0.388
Sodium	11	23	–	0.002	0.000*	-	–
Phosphorus	15	31	–	0.003	–	–	–
Sulfur	16	32	–	0.003	0.008	–	–
Chlorine	17	35	–	0.002	0.000*	–	–
Potassium	19	39	–	0.003	–	–	–
Iron	26	56	–	–	0.000*	–	–
Effective Z			7.22	7.07	7.27	6.52	6.63
%dev. from water			0.00	−2.15	0.64	−9.73	−8.20
%dev. from tissue			2.19	0.00	2.85	−7.75	−6.18

* Elemental constituents of gelatin, while present consist of less than 0.1 %

Table 2 Chemical constituents and percent composition for gels studied

Constituent	Aqueous gel (%)
Gelatin	7.00
C3CA	0.02
Water	92.98
Effective Z	7.226
%dev. from water	0.04
%dev. from tissue	2.24

Percent deviation from water and ICRU 44 soft tissue shown [9]

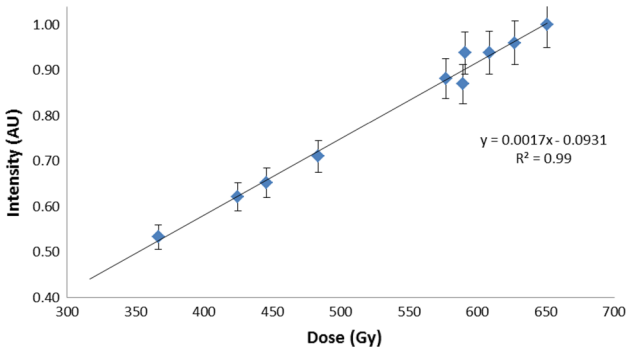

Fig. 2 Average dose plotted versus normalized intensity. Samples at depth were averaged and background subtracted with nominal 5 % relative error bars shown. All four cuvettes were used to derive average values with a 1.5 % relative standard deviation between samples. A linear fit is demonstrated

(Varian Medical Systems; Pal Alto, CA) depth dose data for a 6 MV photon beam to the stacked arrangement of cuvettes. The four cuvettes in each layer were used to derive average values with a 1.5 % relative standard deviation between samples. Average normalized results demonstrate a linear dose response (Fig. 2).

Detector response as a function of depth was fit with a fourth order polynomial (Fig. 3). The fitting of depth dose curves with fourth-order polynomials is an accepted practice that has been shown to provide a reliable fit to experimental and Monte Carlo calculated results [11]. The experimental depth dose curve is consistent with beam models that do not account for contributions from scatter.

Collected data was compared with published beam data (Fig. 4). Varian "Golden Beam Data" (GBD) is derived from The British Journal of Radiology supplement 25 [12]. GBD has been collected under conditions of full scatter while experimental data was collected with cuvettes placed on a table top without side or back-scatter. In the absence

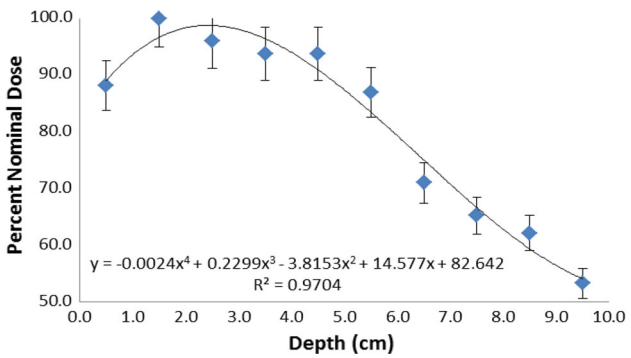

Fig. 3 Illustration of detector response expressed as a percentage of nominal doses normalized to maximum value at 1.5 cm plotted as a function of depth. Error bars represent a nominal 5 % relative error. Curve fit with a fourth order polynomial, $R^2 = 0.9704$

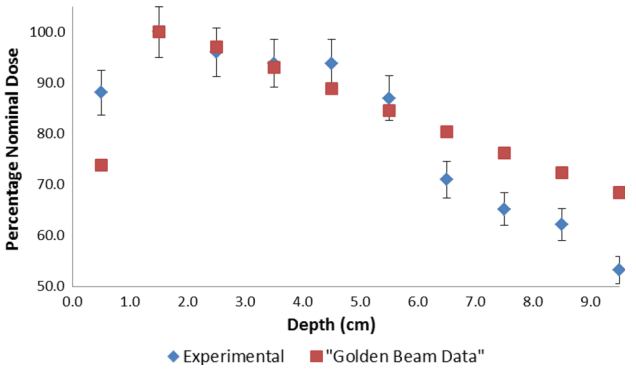

Fig. 4 Plot of nominal dose response as a function of depth. Experimental and "Golden Beam Data" shown, error bars represent nominal 5 % relative error

of scatter the under-response at depth is not surprising. Additionally, volume averaging may have contributed to the lack of agreement of results, with detector response averaged over the entire cuvette thickness (1 cm), assigned to a midpoint (0.5 cm increments) and compared to a point measurement.

Conclusions

The preceding data illustrate the use of a radio-fluorogenic detector exhibiting a measurable dose–response relationship. A water-equivalent radio-fluorogenic gel dosimeter has been produced demonstrating potential for application to quality assurance in radiotherapy. Additional studies investigating spatial dosimetry are warranted. Laser-induced fluorescence is a particularly attractive method for providing high resolution images [13].

Acknowledgments The first author would like to acknowledge the National Institute of Occupational Safety and Health for financial support during the performance of these studies.

References

1. De Deene Y (2004). Essential characteristics of polymer gel dosimeters. J Phys 3(1):34. IOP Publishing
2. Adamovics J, Maryanski MJ (2006) Characterisation of PRESAGE^{TM}: A new 3-D radiochromic solid polymer dosemeter for ionising radiation. Radiat Prot Dosim 120(1–4):107–112
3. Babic S, Battista J, Jordan K (2008) An apparent threshold dose response in ferrous xylenol-orange gel dosimeters when scanned with a yellow light source. Phys Med Biol 53(6):1637
4. Baldock C, De Deene Y, Doran S, Ibbott G, Jirasek A, Lepage M, McAuley KB, Oldham M, Schreiner LJ (2010) Polymer gel dosimetry. Phys Med Biol 55(5):R1
5. Warman JM, de Haas MP, Luthjens LH, Denkova AG, Kavatsyuk O, van Goethem MJ, Kiewiet HH, Brandenburg S (2013) Fixed fluorescent images of an 80MeV proton pencil beam. Radiat Phys Chem 85:179–181
6. Collins AK, Makrigiorgos GM, Svensson GK (1994) Coumarin chemical dosimeter for radiation therapy. Med Phys 21(11): 1741–1747
7. Perry Christopher C, Tang Vicky J, Konigsfeld Katie M, Aguilera Joseph A, Milligan Jamie R (2011) Use of a coumarin-labeled hexa-arginine peptide as a fluorescent hydroxyl radical probe in a nanoparticulate plasmid DNA condensate. J Phys Chem B 115(32):9889–9897
8. Maeyama Takuya, Yamashita Shinichi, Baldacchino Gerard, Taguchi Mitsumasa, Kimura Atsushi, Murakami Takeshi, Katsumura Yosuke (2011) Production of a fluorescence probe in ion-beam radiolysis of aqueous coumarin-3-carboxylic acid solution—1: beam quality and concentration dependences. Radiat Phys Chem 80(4):535–539
9. Tissue Substitutes in Radiation Dosimetry and Measurement (1989) ICRU Report 44. International Commission on Radiation Units and Measurements, USA
10. Zeidan OA, Sriprisan SI, Lopatiuk-Tirpak O, Kupelian PA, Meeks SL, Hsi WC, Li Z, Palta JR, Maryanski MJ (2010) Dosimetric evaluation of a novel polymer gel dosimeter for proton therapy. Med Phys 37(5):2145–2152
11. Lisanti TF (2004) Calculating electron range values mathematically. Radiat Phys Chem 71(1):581–584
12. Aird EGA, Burns JE, Day MJ, Duane S, Jordan TJ, Kacperek A (1996) Central axis depth dose data for use in radiotherapy. Br J Radiol (s25)
13. Sandwall P, Spitz H, Elson H, Lamba M, Connick W, Fenichel H (2014). Radio-fluorogenic dosimetry with violet diode laser-induced fluorescence. In SPIE Medical Imaging. International Society for Optics and Photonics, pp 90333Y-90333Y