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Isodose Curve Mappings Measured While Undergoing Rotation for Quality Assurance Testing of a ^{137}Cs Irradiator

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Abstract

To enable accurate and reproducible dosimetry for biological sample irradiation in a ^{137}Cs irradiator, routine quality assurance (QA) of the dose rate and isodose distributions should be considered. Our previous work demonstrated a means for accurate dose rate QA and for QA of isodose distributions of non-rotational samples. In this work we present a means to accurately and cost effectively measure dose distributions within a ^{137}Cs irradiator using rotational geometry, which geometry represent a more typical use of these irradiators. A simple apparatus was developed to hold radiochromic film (RCF) and was constructed of polymethyl methacrylate (PMMA). The rotational QA device allowed the comparison of measured RCF versus manufacturer provided isodose distributions. A good agreement was discovered between the two data sets along the central vertical axis of rotation in the ^{137}Cs irradiator, but a 40–50% smaller 100% isodose region in the horizontal direction. These finding may lead to limiting the overall size of a sample capable of being uniformly irradiated by the ^{137}Cs irradiator at our research institution. We propose the construction and use of a simple rotational QA device for routine QA of ^{137}Cs irradiators.

Keywords

^{137}Cs Irradiator; dosimetry; Dose response/distribution; Quality assurance/control

INTRODUCTION

Typical ^{137}Cs irradiators provide stable high dose rate irradiation for biological endpoints. To properly irradiate a biological sample within a ^{137}Cs irradiator, an accurate knowledge of the irradiator's dose rate and isodose mapping are essential. The dose rate provides the user of the irradiator a means to calculate the length of time necessary to expose the biological sample to a specific dose point, and the isodose mapping is used to determine where to place the biological sample within the irradiator chamber to achieve the desired dose rate. A means to measure the dose rate and isodose mapping within a particular ^{137}Cs irradiator has been previously reported (Brady et al. 2009). In that report, the methodology demonstrated how to measure an isodose mapping for static sample irradiation (i.e., no sample rotation) and was unable to provide proper comparison to the manufacturer provided isodose data, which was measured while being rotated.

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As a means to facilitate initial acceptance and critical routine quality assurance (QA) testing of ^{137}Cs irradiators, we present a methodology to measure isodose mappings with modern high response sensitivity radiochromic film (RCF) within a ^{137}Cs irradiator using rotational exposure geometry and existing rotational platforms provided with the irradiator.

METHODS and MATERIALS

Irradiator

A Mark I-68A ^{137}Cs irradiator (JL Shepherd and Associates, San Fernando, CA) was used for film exposure and its manufacturer provided isodose data, which were subsequently used for comparison with the measured RCF data. Specific details about the irradiator can be found in Brady *et al.*'s report (Brady et al. 2009). Dose distributions were measured at three locations. Each location corresponded to the location of a motor shaft used to rotate the sample turntables. The three motor shaft positions were labeled 1, 2, and 3; where position 1 was the closest to the source and position 3 the furthest (Fig 1(A)).

Rotational Film Stage

A rotational film stage was developed and manufactured in house and consisted of polymethyl methacrylate (PMMA) that was attached to an existing small (10 cm diameter) copper rotational platform provided by the manufacturer at the time of irradiator installation (Fig 1(B–C)). The γ -ray energy (662 keV) of the ^{137}Cs irradiator required a buildup material to be placed around the film to produce charged particle equilibrium (CPE). Therefore, a plate of PMMA was placed in front and behind the RCF and acted as both a buildup material and structural support for the film. The PMMA material was selected to be 2 mm thick to satisfy CPE requirements calculated using continuous slowing down approximation values for electrons with energies of 662 keV in PMMA (Attix 1986). Two sizes of buildup plates were required to be able to measure the isodose curves at position 1 and then positions 2 and 3. A PMMA base was manufactured to be interchangeable for position 1 buildup plates (10 cm wide) and for positions 2 and 3 (30 cm wide) (Fig 1(B–C)). The base assembly and buildup plates were held together with plastic hand screws. Small holes were cut into the film to allow for the hand screws to pass through the film and secure the rotational film stage together.

Radiochromic Film

In this work, large format EBT RCF (lot # 47261-011 (14×17) inch, International Specialty Products, Wayne, NJ) was used, which allowed for one contiguous piece of film to be exposed *in lieu* of four separate smaller films as previously presented (Brady et al. 2009). Each RCF was exposed for a specific time to produce 7 Gy at the film's central rotational axis. The RCF was digitized using transmission densitometry on an EPSON Expression 10000XL flatbed scanner (Ferreira et al. 2009). Each RCF was scanned at a resolution of 72 pixels per inch (0.4 mm pixels) with no color corrections and saved in uncompressed Tagged Image File Format (TIFF). All films were digitized using 48-bit color depth with RGB file format (16-bit per color channel). The red (R of the RGB) channel was extracted for analysis in MATLAB (R2007a, Mathworks, Natick, MA) since RCF readout sensitivity has been shown to be optimized using red light due to the films reported absorption spectrum maximum at 635 nm (Devic et al. 2007). The final image was smoothed using a 2-D Wiener filter with a 3×3 pixel kernel (Devic et al. 2009). Once irradiated, the films darkened such that their optical density (OD) exponentially increased with exposure; the reaction occurred in real-time. The films were allowed 6 hours for the polymerization reaction to induce negligibly small increases in OD (Cheung et al. 2005). Net OD (netOD) was calculated as the log transformation of the ratio of pre-irradiation (I_{pre}) and post-irradiation (I_{post}) scanner light intensity values (Devic et al. 2005):

$$netOD = OD_{post} - OD_{pre} = \log_{10} \left(\frac{I_0}{I_{post}} \right) - \log_{10} \left(\frac{I_0}{I_{pre}} \right) = \log_{10} \left(\frac{I_{pre}}{I_{post}} \right), \quad (1)$$

where I_0 was the measured light intensity measured before transmission through the film. The films were calibrated to associate their netOD readout response with absorbed dose measured by a 0.18 cc ion chamber (Radcal, Monrovia CA). In this work, similar film calibration techniques were employed as were reported previously (Brady et al 2009). In brief the calibration curve was developed from five pieces of film. Each piece was irradiated at different exposure levels alongside the ion chamber, namely: 0, 158.0, 339.6, 493.2, and 797.6 X(R). A Plexiglas buildup plate was placed to surround the EBT film to provide proper CPE. The films were set on top of a Styrofoam block (with the surface of the films set perpendicular to the main axis of the ^{137}Cs source) so that the film and ion chamber were surrounded by air. The film/ion chamber combination was placed at a height within the irradiator cavity so that it was within the same isodose region. The films used for calibration were allowed the same amount of film stabilization time for equal OD growth as the dose distribution films. The calculated absorbed dose values were plotted versus the film netOD values and the data were fit using a modified exponential curve of the form:

$$Dose_{air}(cGy) = a \cdot (e^{b \cdot netOD} - 1). \quad (2)$$

A Levenberg-Marquardt algorithm was written to optimize the coefficients a and b shown in Eq. (2).

RESULTS and DISCUSSION

The resulting netOD distributions measured for positions 1–3 were calibrated to display absorbed dose distributions in air by using the fitting function relationship derived in Fig 2. The calibration error at the film irradiation level of 7 Gy was calculated to be 2%. The dose distributions (Fig 3(A,D,G)) were converted to isodose curves (Fig 3(B,E,H)) where the points of normalization (100% relative dose value) were set to reflect the same locations established by the manufacturer as determined from the manufacturer provided data (Fig 3(C,F,I)). Additionally, vertical (Fig 4(A,C,E)) and horizontal (Fig 4(B,D,F)) line profiles were sampled from the measured isodose plots of positions 1–3 to compare the measured isodose curves with the manufacturer provided isodose curves. Of the measured vertically sampled data points, 31 out of 38 measured differences $\leq 5\%$ of the manufacturer provided data. Position 1 had an average difference of 3% (range 0–10%) with 17 out of 20 data points $\leq 5\%$; position 2 had an average difference of 6% (range 0–20%) with 6 out of 10 data points $\leq 5\%$; and position 3 had an average difference of 3% (range 0–5%) with 8 out of 8 data points $\leq 5\%$. The measured vertical data points demonstrating $\leq 5\%$ difference with the manufacturer provided data spanned ~90% of the inner irradiator cavity dimension. Most all discrepancies $> 5\%$ were found at the extreme top and at the lowest 3 cm of the film; where the one exception was measured at 17 cm at position 1 (Fig 3(A)). The data discrepancies at the lowest 3 cm of the film were due to greater γ -ray attenuation stemming from a region where extra Plexiglas was used to secure the film holder to the rotational platform (the location where four holes can be seen in the films, Fig 3(A,D,G)).

The horizontally sampled data points for positions 1–3 demonstrated increased absorbed dose as a function of radial distance away from the central vertical axis of the film. Position 1 had an average difference of 7% (range 0–20%) with 5 out of 8 data points $\leq 5\%$. The discrepancies in data sets for position 1 are ascribed to the asymmetric data measured at position 1 (Fig 3(A) and Fig 4(B)), which is most likely due to a rotational time averaging

effect. The dose rates at position one require a shorter film exposure time (0.37 min) compared to that of positions 2 (1.67 min) and 3 (2.36 min), so that one side of the film has the potential to spend more time nearer to the sources than the other. In the future, position 1 should be exposed to dose levels 2–3 times that of positions 2 and 3 to provide a more even rotational signal averaging. Recently, a scientific paper has demonstrated (Devic et al. 2009) how to accurately measure radiation doses up to 100 Gy for EBT RCF dosimetry. EBT RCF would support the longer exposure times proposed for position one films.

Positions 2 and 3 demonstrated horizontally-symmetrical rotational data about the central vertical axis, but a greater rate of increase in relative dose as a function of radial distance. The average measured difference compared to the manufacturer data was 26% (0–50%) and 29% (5–60%) for positions 2 and 3, respectively. The increased relative dose along the outer edges of the film is due to the film edges being rotated so that they pass very near the source-tube where the two ^{137}Cs sources were located; the positions of the ^{137}Cs sources are clearly demonstrated in Fig 3(A,D) by the two distinct hot spots at the top and bottom of the film's outer edges. When accounting for the steeper rate of relative dose per distance change, compared with the manufacturer provided data, the measured radiation distribution demonstrated smaller sizes of the 100% isodose region by ~40–50%; for position one, the physical distance of the 110% isodose region (the largest uniform isodose region at position 1) remained the same.

CONCLUSION

In this work we have demonstrated a simple means to provide initial acceptance and routine QA testing for dose distribution mapping of a ^{137}Cs irradiator. Some commercial products are available for isotope irradiator QA; however, these devices are not designed to meet the specific needs of testing the irradiator at varying distances from the source, which is often the case in ^{137}Cs irradiators. By manufacturing a simple PMMA rotational film stage, QA testing of isodose curves can be tailored to fit the needs of individual radiobiological facilities. Additionally, PMMA is relatively inexpensive where the material cost for the rotational film stage presented in this work was less than \$30 US dollars.

In this work, the rotational QA device employing RCF dosimetry demonstrated a good agreement between the manufacturer provided and measured data along the central vertical axis of rotation in the ^{137}Cs irradiator, but a 40–50% smaller 100% isodose region in the horizontal direction. These findings may lead to limiting the overall size of a sample capable of being uniformly irradiated by the ^{137}Cs irradiator at our research institution.

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Biography

Samuel Brady is a staff medical physicist at St. Jude Children's Research Hospital in Memphis TN USA. He received his masters and PhD degrees from Duke University. His clinical and research expertise is in the areas of experimental radiation dosimetry.

Figure 1.

(A) The ^{137}Cs irradiator is equipped with three rotational stages, labeled positions 1–3 respectively. Each position is located at increasing distance from the source guide channel where the cesium sources enter the irradiation channel. A rotation film stage assembly was designed to attach to an existing rotational platform provided by the manufacturer. Two millimeter thick PMMA plates were placed in the front and back of the radiochromic film and used to provide structural support and to establish proper charged particle equilibrium for the film. Two PMMA plate sizes were designed to be interchangeable with the base assembly: (B) small 10 cm wide plates for measurements at position 1, closest to the ^{137}Cs source, and (C) large 30 cm wide plates for isodose curve measurements at positions 2 and 3.

Figure 2.

(A) The radiochromic film was calibrated using the methodologies outlined in Brady *et al.* 2009 and fit using a modified exponential function to account for netOD parameters. (B) Fitting errors between the data and the exponential fitting function in (A) are demonstrated. The calibration error at the dose level in which the films were exposed (7 Gy) was 2%.

Figure 3. (Left column) Dose distributions are shown for position 1–3. (Middle column) Dose distributions were converted to isodose curves for a comparison with (Right column) the manufacturer provided data.

Figure 4. Vertical and horizontal line profiles were taken along the dotted lines in Fig 3(A,D,G) and plotted along with corresponding manufacturer provided data for positions 1–3, respectively.