Sensitivity calibration procedures in optical-CT scanning of BANG[®]3 polymer gel dosimeters

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The dose response of the BANG[®]3 polymer gel dosimeter (MGS Research Inc., Madison, CT) was studied using the OCTOPUS[™] laser CT scanner (MGS Research Inc., Madison, CT). Six 17 cm diameter and 12 cm high Barex cylinders, and 18 small glass vials were used to house the gel. The gel phantoms were irradiated with 6 and 10 MV photons, as well as 12 and 16 MeV electrons using a Varian Clinac 2100EX. Three calibration methods were used to obtain the dose response curves: (a) Optical density measurements on the 18 glass vials irradiated with graded doses from 0 to 4 Gy using 6 or 10 MV large field irradiations; (b) optical-CT scanning of Barex cylinders irradiated with graded doses (0.5, 1, 1.5, and 2 Gy) from four adjacent 4×4 cm² photon fields or 6×6 cm² electron fields; and (c) percent depth dose (PDD) comparison of optical-CT scans with ion chamber measurements for 6×6 cm², 12 and 16 MeV electron fields. The dose response of the BANG[®]3 gel was found to be linear and energy independent within the uncertainties of the experimental methods (about 3%). The slopes of the linearly fitted dose response curves (dose sensitivities) from the four field irradiations ($0.0752 \pm 3\%$, $0.0756 \pm 3\%$, $0.0767 \pm 3\%$, and $0.0759 \pm 3\%$ cm⁻¹ Gy⁻¹) and the PDD matching methods ($0.0768 \pm 3\%$ and $0.0761 \pm 3\%$ cm⁻¹ Gy⁻¹) agree within 2.2%, indicating a good reproducibility of the gel dose response within phantoms of the same geometry. The dose sensitivities from the glass vial approach are different from those of the cylindrical Barex phantoms by more than 30%, owing probably to the difference in temperature inside the two types of phantoms during gel formation and irradiation, and possible oxygen contamination of the glass vial walls. The dose response curve obtained from the PDD matching approach with 16 MeV electron field was used to calibrate the gel phantom irradiated with the 12 MeV, 6×6 cm² electron field. Three-dimensional dose distributions from the gel measurement and the Eclipse planning system (Varian Corporation, Palo Alto, CA) were compared and evaluated using 3% dose difference and 2 mm distance-to-agreement criteria. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3298017](https://doi.org/10.1118/1.3298017)]

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I. INTRODUCTION

An accurate and robust sensitivity calibration procedure is essential for the use of a dosimeter in routine clinical practice of radiation therapy. Among the dosimeters that are currently used in radiation physics, ion chambers are required to be calibrated at the accredited dosimetry calibration laboratories on a regular basis. TLDs and films are normally calibrated along with each dose measurement process by irradiating a series of dosimeters (TLDs or films) from the same batch to known graded doses. This procedure is based on the assumption that the dose response curves of the dosimeters used in a dose verification process are all identical. For dose measurements using 3D dosimeters, the calibration procedure using multiple dosimeters of the same geometry may not be efficient enough considering the rich dosimetric information that 3D dosimeters can provide.

In recent years, the so-called gel dosimeter has emerged as a promising candidate for 3D dosimetry.^{1–13} Extensive

studies have been done on the development of different types of gel formulas,^{1,3,14–19} implementation of various imaging modalities for gel dosimetry,^{1,2,20–24} and technical advantages and difficulties associated with 3D dosimetry.^{10,25,26} Gel dosimetry has been used for dose verifications from photon, electron, and proton beam irradiations.^{23,27–29} Results from the gel measurements have been analyzed and compared with treatment planning systems and other dosimeters.^{23,30,31}

In the early investigations of gel dosimetry, the dose responses of the dosimeters were usually obtained from measurements across a series of small size dosimeters irradiated to graded doses.^{4,8,9} The resultant dose response curve could then be used to calibrate the dose response of large gel phantoms.^{27,28,32} Preliminary results on the use of multiple small photon fields, Ir¹⁹² high dose rate irradiations, and electron depth dose curves for sensitivity calibration were also reported.^{9,33–35} These methods were used in conjunction with various imaging methods, including optical-CT and MRI.

Since the invention of the polymer gel dosimeter in 1993,¹ the BANG[®] gel dosimeter has been widely studied, particularly in conjunction with optical-CT. The dose response mechanism, the temperature effect, and the optical properties of the BANG[®] gel dosimeter were analyzed systematically.^{1,4} This forms the basis for the manufacturing and the improvement of the dosimeter.^{9,35,36} Attempts were also made to study the dose rate dependence and the energy dependence of the BANG[®] gels.^{28,37} The gel formula has been continuously updated to accommodate the needs for studies in wide dose range from different therapy units.^{4,14,36}

The purpose of this study is to find an accurate and convenient procedure for sensitivity calibration in optical-CT-based gel dosimetry using BANG[®]3 polymer gel dosimeters. To achieve this goal, we apply three calibration methods to study the dose response of the BANG[®]3 polymer gel and compare their performances. The methods include (a) measurements across a series of small size dosimeters irradiated to graded doses; (b) optical-CT scanning of a single gel phantom irradiated to graded doses with multiple small fields; and (c) percent depth dose comparison between optical-CT scans and ion chamber measurements for single electron field.

II. MATERIALS AND METHOD

II.A. BANG[®]3 polymer gel and phantoms

The BANG[®]3 polymer gel is a tissue-equivalent gel made of gelatin, water, and methacrylic acid. Radiation doses can be recorded in a gel phantom as the polymer microparticles produced from radiation induced polymerization. The distribution of polymer microparticles inside a gel phantom normally becomes stable within 30 min from irradiation and remains “readable” for at least a couple of weeks.²³ It takes months for the cumulative increase in the background polymerization to affect the recorded dose distribution in a gel phantom by a few percent. The dose response curve of the BANG[®]3 gel in principle consists of a linear region followed by a saturation region.^{3,11} By varying the weights of different components of the gel and/or adding millimolar quantities of sensitivity reducing agents such as ferrous sulfate,³⁶ the saturation region of the gel can always be adjusted to be well above the dose range studied. The saturation level of the gel used in this study was set to be more than 8 Gy.

The gel phantoms used in this study are glass vials of 8 cm length and 2.4 cm inner diameter and 17 cm diameter $\times$ 12 cm high cylinders thermoformed from 1 mm thick Barex plastic sheet (CIRS, Norfolk, VA) (see Fig. 1). Before the gel phantoms were made, oxygen was removed from the containers by bubbling nitrogen gas through the gel containers for prolonged time. The BANG[®]3 gel was mixed in a large chemical reactor and poured into containers at room temperature. It took less than 24 h for the gel to solidify in the containers.

FIG. 1. BANG[®]3 polymer gel phantoms used in this study: (a) Glass vials of 8 cm length and 2.4 cm inner diameter; (b) Barex cylinders of 17 cm diameter and 12 cm height.

II.B. Irradiation of gel phantoms

The experiments performed were with 18 glass vials and six Barex cylinders. The gel phantoms were filled with gel from the same batch and irradiated with multiple photon and electron fields in the clinical dose range using a Varian Clinac 2100EX. Both the Barex cylinders and the glass vials were immersed in a $24 \times 24 \times 20$ cm³ water tank during the irradiation process. The edges of the water tank were parallel to the alignment laser beams. The gantry, couch, and collimator angles were zero unless otherwise specified.

The gel phantoms used in this study were placed in the treatment area (at a constant temperature of 21 °C) for about 24 h before the irradiations. The glass vials were stood upright in the center of the water tank and irradiated from the bottom of the water tank with a gantry angle of 180°; 16 glass vials were put in the center of a 20×20 cm² light field one by one and irradiated with 6 or 10 MV photons. The doses delivered were 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 Gy at Dmax, respectively. Two unirradiated glass vials were used for background readouts.

Each of the six gel cylinders was put in the water tank such that the flat bottom of the cylinder was in direct contact with the right side of the tank. Radiation was delivered through the flat bottom of the gel cylinder with a gantry angle of 270°. The first two gel cylinders were irradiated with 6 and 10 MV photons, respectively, using a SAD setup (with a fixed source-to-axis distance of 100 cm). Four 4×4 cm² single field irradiations were delivered to each phantom, with maximum doses of 0.5, 1, 1.5, and 2 Gy. Each photon field was confined to one quadrant of the gel cylinder. The gap between the edges of the adjacent fields was 2 cm at the surface of the water tank. The third and the fourth gel cylinders were irradiated with 12 and 16 MeV electrons, respectively, using a SSD setup (with a fixed source-to-surface distance of 100 cm). Four 6×6 cm² single field irradiations were delivered to each phantom, with maximum doses of 0.5, 1, 1.5, and 2 Gy. The gap between the edges of the adjacent fields was reduced to 1 cm. The fifth and the sixth gel cylinders were irradiated with 12 and 16 MeV electrons using the same SSD setup. Only one 6×6 cm² electron field was delivered to the central region of each phantom (with a maximum dose of 2 Gy).

II.C. Extraction of dose response curves

In this work, we used the OCTOPUSTM laser CT scanner (MGS Research Inc., Madison, CT) to measure the optical density drops across the glass vials and the optical density distributions within the Barex gel cylinders. The basic operating principle and the prototype configuration of this scanner were described previously.^{2,9,19,22} A comprehensive analysis of the performance of the scanner and its accuracy in reproducing 3D optical attenuations can be found in Ref. 23.

The unit length optical density value corresponding to the maximum dose delivered to a glass vial was obtained from scanning the cross section of the glass vial at the depth that corresponds to the Dmax of the photon field used. Specifically, the laser intensity drop along the laser path passing through the central axis of the glass vial at Dmax was obtained and averaged over the path length (2.4 cm inner diameter of the glass vials). The measurements were done one day after the irradiations. Each glass vial was stood upright on the center of the turntable within the scanning tank filled with a liquid mixture of water, glycerol, and a blue dye.²³ The laser beam was adjusted to the Dmax position of the glass vial and programmed to scan across the tank. The smallest signal in the acquired projection data was identified and divided by the laser signal in the same pixel of the projection data without a glass vial. The glass vial was then rotated 60° and the procedure was repeated. The optical density value across the glass vial over the 2.4 cm laser path length was then calculated as the average of the six readings obtained.

The six irradiated cylindrical gel phantoms were scanned with 1 mm pixel size, 200 pixels per projection, 300 projections per slice (for a total rotation angle of 180°), and a slice separation of 2 mm. The slice thickness was about 0.6 mm (diameter of the laser beam). The phantoms were scanned within four days after the irradiations, with a scanning time of about 8 h for each phantom (60 slices). The optical density distributions inside the gels were reconstructed by using the filtered back projection algorithm. The uncertainty (defined as the ratio between the standard deviation and the mean value) of the reconstructed optical density values is about 3%.²³ For the four field irradiations with 6 and 10 MV photons, the reconstructed images from Dmax to 10 cm depth were used to obtain the dose response curves. Only the reconstructed images at Dmax were analyzed for the four field irradiations with 12 and 16 MeV electrons. The reconstructed unit length optical density corresponding to a delivered dose was taken as the average over a circle of 0.8 cm diameter (about 50 pixels) in the central region of the square fields using the IMAGEJ software (<http://rsb.info.nih.gov/ij>). For the single field irradiations with 12 and 16 MeV electrons, the averaged unit length optical density values at different depths were obtained in the same way. The optical density values obtained for each energy were then matched with the central axis depth doses from ion chamber measurements from Dmax to the depth of 3% dose.

FIG. 2. Dose response curves of the BANG[®]3 gel obtained from the glass vial approach with 6 MV (solid line) and 10 MV (dashed line) irradiations. The error bars indicate an experimental uncertainty (defined as the ratio between the standard deviation and the mean value) of 6%.

II.D. Treatment planning and dose comparison

For the four field irradiations, the number of monitor units for the 4 × 4 cm² photon field or the 6 × 6 cm² electron field was calculated from an in-house dose calculation program for the 0.5, 1, 1.5, and 2 Gy doses. In order to estimate the maximum contribution of peripheral doses from neighboring fields on the optical density values taken at different depths, the geometry of the four field irradiations was reproduced in the Eclipse treatment planning system using an artificial water phantom. 3D dose distributions were calculated for each beam arrangement with only the 4 × 4 cm², 0.5 Gy square field and with all the four fields together. The total peripheral dose at the central region of the 4 × 4 cm², 0.5 Gy field was then taken as the difference.

The single field irradiation with 12 MeV electrons was planned on the Eclipse treatment planning system. The resultant 3D dose distribution was exported to an in-house dose comparison computer program written with MATLAB (The Math Works Inc., Natick, MA) and compared with the gel measurement. The gel dose distribution for this irradiation was calibrated using the dose response curve obtained from percent depth dose (PDD) matching of the 16 MeV electron field. Linear interpolation or extrapolation of the dose response curve was performed when needed. Gamma analyses were performed in the computer program between the planned and the measured dose distributions for the 6 × 6 cm², 12 MeV electron field irradiation using 3% dose difference and 2 mm distance-to-agreement criteria.

III. RESULTS AND DISCUSSION

III.A. Glass vial measurements

Figure 2 shows the dose response curves for 6 MV (solid circles) and 10 MV (open circles) photons obtained from the glass vial experiments. The optical density values for these two energies at the same doses differ from less than 1%–15%, indicating a large uncertainty in the values obtained. The experimental points for the two energies can be fitted to straight lines with R^2 values of 0.989 and 0.991. The slopes

FIG. 3. Reconstructed images from the four field irradiations: (a) Four 4×4 cm² photon fields; (b) four 6×6 cm² electron fields; (c) line profile along the dashed line in (a); (d) line profile along the dashed line in (b).

and the background optical densities of the dose response curves are different by 6.5% and 8.8%, respectively. These differences can be attributed to the large experimental uncertainty of the glass vial approach. During measurement of the optical density values across the glass vials using the optical-CT scanner, we observed that the readouts were sensitive to the orientation of the laser path relative to the glass vials. The inaccuracy in the positioning of the laser beam at the depth of maximum dose within each glass vial could also contribute to the large experimental uncertainty. The maximum difference among the six readings taken for one glass vial was found to be 15%. The ratio between the standard deviation and the mean value for the group of six readings taken from a glass vial could be as much as 6%.

III.B. Four field irradiations

Figure 3 contains sample transverse images from scanning gel cylinders irradiated with four photon or electron fields. The planned field arrangements and the position of the containers are easily identifiable from these images. The shapes of the photon and the electron fields are also well reproduced.

As is shown in Figs. 3(c) and 3(d), the reconstructed images close to the container wall exhibit a systematic intensity drop, indicating a substantial loss of laser signal in these regions because of the imperfect matching of the refractive index of the gel, the container wall, and the matching liquid.²³ The faint straight lines connecting the corners of the adjacent square fields are imaging artifacts caused by the increased refractive index with polymerization. When the laser beam is tangential to the edges of the square fields, the difference of the refractive index around the field edges will cause the beam to bend outward and miss the detector. This artifact is more pronounced with higher degrees of polymerization and with increased number of polymerized edges along the laser path.

FIG. 4. Dose response curves of the BANG[®]3 gel obtained from the four field irradiations. A 3% uncertainty in the reconstructed optical density values is indicated by the error bars. The reconstructed images from Dmax to 10 cm depth were used for the photon field irradiations. Only the reconstructed images at Dmax were analyzed for the electron field irradiations.

Figure 4 plots the reconstructed unit length optical density value versus the delivered dose for the four field irradiations. The dose response of the BANG[®]3 polymer gel is demonstrated to be linear and energy independent in the dose range studied, as was observed in previous studies using both optical-CT and MRI.^{3,4,9,28,30,37} The slopes of the linearly fitted dose response curves are $0.0752 \pm 3\%$, $0.0756 \pm 3\%$, $0.0767 \pm 3\%$, and $0.0759 \pm 3\%$ cm⁻¹ Gy⁻¹ for the 6 MV, 10 MV, 12 MeV, and 16 MeV irradiations, respectively. The corresponding R^2 values are 0.9992, 0.9996, 0.9985, and 0.9983. The dose sensitivities from the four field irradiations are different from those of the glass vial experiments by more than 30%.

The reconstructed optical density value for each square field at certain depth was taken as the average over a circular region of 0.8 cm diameter in the center of the field. Typically a standard deviation of less than 1.5% was observed for the averaged values. From the Eclipse planning system, it was estimated that the total peripheral dose from the square field irradiations with 1, 1.5, and 2 Gy maximum doses at the center of the 4×4 cm², 0.5 Gy square field (at Dmax) was 0.35, 0.38, 0.42, and 0.49 cGy for the 6 MV, 10 MV, 12 MeV, and 16 MeV irradiations, respectively. The contributions of peripheral doses to the optical density values at Dmax are therefore less than 1% for all the four field irradiations. With increasing depths, however, the peripheral doses in the phantoms increase substantially for the four electron field arrangements. The maximum peripheral dose at the center of the fields at 8 cm depth could be as much as 12% of the primary dose. The contribution of peripheral dose to the optical density values does not change much with depth for the four photon field irradiations. Therefore, optical density values at an interval of 1 cm depth were taken only for the four field irradiations with photons, to maintain an overall accuracy (defined as the ratio between the standard deviation and the mean value) of 3% for the obtained optical densities and dose response curves.²³

FIG. 5. Reconstructed images from the 12 MeV, 6×6 cm² electron field irradiation: (a) Transverse slice at 3.5 cm depth; (b) coronal slice that passes through the isocenter.

III.C. PDD matching for single electron field

In Fig. 5, we show two reconstructed images from the 12 MeV, 6×6 cm² electron field irradiation. The black lines in the central regions of the images encompass the area where the unit length optical density values were taken. As was the case for the four field irradiations, an averaged optical density value over a circular region of 0.8 cm diameter on the reconstructed transverse image was used for each depth. When the radius of this circle was varied from 0.5 to 2 cm, variation of less than 2% was observed in the averaged optical density value.

Figure 6 contains the dose response curves as determined from the PDD matching between the gel measurement and the ion chamber measurement for the 12 and 16 MeV electron field irradiations. Even though phantoms of the same size were used, twice as many points were obtained from the 16 MeV square field than from the 12 MeV square field in the dose range from 6 to 2 Gy. This was expected because the portion of the percent depth dose curve for the 16 MeV electron field from maximum dose to 3% dose expands a much wider range than that of the 12 MeV electron field. The dose sensitivities obtained ($0.0768 \pm 3\%$ cm⁻¹ Gy⁻¹ for 12 MeV electrons and $0.0761 \pm 3\%$ cm⁻¹ Gy⁻¹ for 16 MeV electrons) agree with those from the four field irradiations ($0.0752 \pm 3\%$, $0.0756 \pm 3\%$, $0.0767 \pm 3\%$, and $0.0759 \pm 3\%$ cm⁻¹ Gy⁻¹) within 2.2%.

FIG. 6. Dose response curves of the BANG[®]3 gel obtained from the PDD matching method. A 3% uncertainty in the reconstructed optical density values is indicated by the error bars.

FIG. 7. Central axis depth dose comparison between gel measurement and ion chamber measurement for the 12 MeV, 6×6 cm² electron field.

Figure 7 compares the central axis depth dose curve from the gel measurement with that from the Eclipse planning system for the gel irradiated with the 6×6 cm², 12 MeV electron field. The gel dose distribution was calibrated using the dose response curve obtained from the PDD matching for 16 MeV, 6×6 cm² electrons (red line in Fig. 6). The maximum dose difference between the measurement and the planning system was 3.4% at 4.5 cm depth.

Figure 8 compares the dose distributions from the gel measurement and the Eclipse planning system for one transverse and one coronal slice of the gel irradiated with the 6×6 cm², 12 MeV electron field. The 3D gel dose distributions were obtained using the dose response curve from the 16 MeV, 6×6 cm² single field irradiation (red line in Fig. 6). All the features of the planned dose distributions were well reproduced in the gel experiment. The gamma values are in general larger in the high dose and low dose regions and along the diagonals of the square field. More than 97% of the pixels pass the 3% dose difference and 2 mm distance-to-agreement criteria in the dose region from 10 to 200 cGy. There appear to be a stripe pattern in the gamma maps and some small wiggles in the measured isodose lines. These structures represent a fluctuation of less than 2% in certain regions of the gel dose distributions and could be resulted from the nonuniformity of the water tank wall, the container wall, and the gel material.

III.D. Discussion

Sensitivity calibration for the measurement of 3D dose distributions using gel dosimetry can be done at least in three ways: To measure the dose responses of a series of phantoms of smaller size filled with gel from the same batch; to deliver a predefined standard calibration pattern to an isolated region of the phantom containing the dose distribution studied; or to use a separate phantom of the same geometry for calibration.

The calibration approach using small size dosimeters was introduced primarily for the purpose of obtaining the dose response curve of a gel formula in a timely and convenient fashion. It is particularly useful during the development of new gel formulas when extensive studies are needed with regards to the dependence of gel sensitivity on ingredient change and environment change. Implementation of this approach for dose measurement using BANG[®]3 gel dosimeters should be based on a clear indication of identical gel dose

FIG. 8. Comparison of the isodose lines (198, 180, 160, 120, 80, and 40 cGy) from the gel measurement (red lines) and the treatment plan (black lines) for the 12 MeV, 6×6 cm² electron field: (a) Transverse slice at 3.5 cm depth; (b) coronal slice that passes through the isocenter; (c) gamma map for (a); (d) gamma map for (b).

response in phantoms of different shapes and sizes. This phenomenon was not observed in the present study and needs further investigation. The dose sensitivities as determined from the glass vial approach and the large gel cylinder experiments in this study are different by more than 30% for the same batch of gel. This difference could be attributed to the difference in the temperature inside the two types of phantom during gel formation and irradiation,^{38,39} and possible oxygen contamination of the glass vial walls. Residue oxygen close to the container wall may suppress the gel dose response in these peripheral regions and result in smaller optical density readouts for the same doses delivered. Furthermore, the cylindrical glass vials used in the present study do not provide an area of equal laser path length for averaging. This limits the overall accuracy and stability of the experimental method. Optical cuvettes with flat surfaces might be a better candidate for future study of the calibration approach using small size dosimeters.³¹

The second calibration method is to divide a gel phantom into two regions, one for the dose distribution to be measured

and one for calibration irradiation. Preliminary results were reported on the use of three pencil beams to calibrate a 3D conformal dose distribution irradiated to the same phantom in the context of cone beam CT-based gel dosimetry.⁴⁰ This approach eliminates the uncertainties associated with the gel dose responses in different phantoms but relies on the existence of a well isolated calibration region in the gel phantom studied. For the study of noncoplanar or nonisocentric irradiations, the peripheral doses from the studied irradiations to the calibration distribution might cause considerable experimental error.

Calibration approaches using a separate phantom require good reproducibility of the gel dose response within phantoms of the same geometry, as is demonstrated for the BANG[®]3-Barex gel phantom. A four field arrangement was chosen for the multiple-field approach in this study mainly for two considerations. First, the field size should be large enough to avoid the dosimetric difficulties with small fields and to provide sufficiently large areas for averaging. Second, the fields should be separated far enough to minimize the

effect of peripheral doses from adjacent fields. As such, the number of experimental points available for a phantom of certain size in a multiple-field irradiation approach is often limited. The multiple photon field irradiations cannot provide reconstructed optical densities for all desired dose values, especially for low doses. The four field irradiations with electrons further suffer from the peripheral dose issue at large depths. Nevertheless, the four field irradiations in this study demonstrate that the energy dependence of the BANG[®]3 gel is not observable within the experimental uncertainty. This provides a basis for the more convenient and more accurate PDD matching method.

To minimize the experimental uncertainty with the PDD matching method, it is desirable that the two gel phantoms for calibration and study purposes be made, stored, and irradiated in the same temperature environment. Identical experimental setup and scanning parameters should be used to scan the two phantoms, including a consistent method for the normalization of all projection data. For instance, the optical attenuation property of the matching liquid can be adjusted such that for all the projections acquired, the maximum signal is always detected when the laser scans directly through the matching liquid. At the image reconstruction stage, the projection data can then be normalized to such a maximum, which does not change with phantoms and slices. For scanning time long enough to affect the battery strength of the photodiode detector, monitoring of the laser output, and correction of the detected signals with a reference detector may also be necessary.

For optimum performance of the PDD matching method, a 16 MeV electron field with a field size of larger than 6 cm is desired. The maximum dose for the electron field irradiation should be larger than the anticipated maximum dose in the dose distribution studied. Unit length optical density value can be obtained from each reconstructed transverse image as an average over a circular region of about 1 cm diameter in the central region of the electron field. A one-to-one correspondence between the obtained unit length optical density values and the delivered doses from ion chamber measurements is then established for all the available slices from D_{max} to the depth of 3% dose. Curve fitting can be performed to obtain the dose response curve for the dose range studied.

IV. CONCLUSIONS

We have studied the dose response property of the BANG[®]3 gel in the therapeutic energy range using 6 and 10 MV photon field, and 12 and 16 MeV electron field irradiations and BANG[®]3 gel samples from the same batch. The optical response of the BANG[®]3 gel was found to be linear and energy independent within the uncertainty of the experimental method used. The dose response curves obtained from the six Barex gel phantoms agree within 2.2%, indicating a good reproducibility of the gel dose response within phantoms of the same geometry. The dose sensitivity of the BANG[®]3 gel obtained from the small glass vial experiment was substantially different from that of the large Barex phan-

toms, owing possibly to the difference in temperature inside the two types of phantoms during gel formation and irradiation, and possible oxygen contamination of the glass vial walls.

Based on the energy independence and the dose response reproducibility established for the BANG[®]3-Barex gel phantoms, the PDD matching method using electron depth dose curve from ion chamber measurement as a benchmark is demonstrated to be a convenient and accurate way for dose response calibration in optical-CT scanning of BANG[®]3 gel dosimeters. A 16 MeV electron field irradiation with a field size of larger than 6 cm is appropriate for this purpose. The calibration method using multiple small-field irradiations is in general more labor intensive and less accurate than the PDD matching approach in that it cannot provide optical density values for all desired doses. Cautions need to be taken with the dose sensitivity calibration method using small glass vials irradiated to graded doses in optical-CT of BANG[®]3 gel.

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