A method to improve accuracy and precision of water surface identification for photon depth dose measurements^{a)}

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The objective of this study is to present a method to reduce the setup error inherent in clinical depth dose measurements and, in doing so, to improve entrance dosimetry measurement reliability. Ionization chamber (IC) depth dose measurements are acquired with the depth scan extended into the air above the water surface. An inflection region is obtained in each resulting percent depth ionization (PDI) curve that can be matched against other measurements or to an inflection region obtained from an analogous Monte Carlo (MC) simulation. Measurements are made with various field sizes for the 6 and 18 MV photon beams, with and without a Pb foil in the beam, to determine the sensitivity of the dose inflection region to the beam conditions. The offset between reference and test data set inflection regions is quantified using two separate methods. When comparing sets of measured data, maxima in the second derivative of ionization are compared. When comparing measured data to MC simulation, the offset that minimizes the sum of squared differences between the reference and test curves in the ionization inflection region is found. These methods can be used to quantify the offset between an initial setup (test) position and the true surface (reference) position. The ionization inflection location is found to be insensitive to changes in field size, electron contamination, and beam energy. Data from a single reference condition should be sufficient to identify the surface location. The method of determining IC offsets is general and should be applicable to any IC and other radiation sources. The measurement method could reduce the time and effort required in the initial IC setup at a water surface as setup errors can be corrected offline. Given a reliable set of reference data to compare with, this method could increase the ability of quality assurance (QA) measurements to detect discrepancies in beam output as opposed to discrepancies in IC localization. Application of the measurement method standardizes the procedure for localizing cylindrical ICs at a water surface and thereby improves the reliability of measurements taken with these devices at all depths. © 2009 American Association of Physicists in Medicine. [DOI: [10.1118/1.3098125](https://doi.org/10.1118/1.3098125)]

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I. INTRODUCTION

Acquisition of depth ionization measurements at each beam energy for each radiotherapy treatment accelerator is a routine clinical task required during both initial commissioning and annual quality assurance (QA). The depth ionization data are input to the treatment planning system, which then either uses the data directly to compute treatment doses, or indirectly to fit algorithms which are then used for dose calculation. In setting up a water phantom, initial surface localization with respect to the ionization chamber (IC) is a primary concern since any errors in the surface identification result in a systematic error for all future uses of the measurement data. Surface identification is particularly challenging for cylindrical ICs. A recent AAPM taskgroup¹ recommends a method of looking at the IC reflection from beneath the surface and setting zero depth at the point where the reflected image and the cylindrical IC form a perfect circle. While this

method will allow one to get close to properly matching the IC center with the water surface, this is still a qualitative determination. The fact is that although manufacturers, the AAPM,¹⁻⁶ and others⁷⁻⁹ made several recommendations regarding procedures for depth ionization data acquisition, this process remains partly science, partly art. In addition, proper IC localization requires corrections such as those to account for the effective point of measurement (EPOM). Identification of the depth origin (typically, the surface of a water phantom) relies on operator's technique, skill, and patience. Due to this, ionization values in the entrance region are lightly regarded and infrequently clinically utilized.

However, the entrance ionization region contains valuable information for the commissioning of dose calculation algorithms. Differences between measurements and calculations in the entrance region, particularly for 18 MV $40 \times 40 \text{ cm}^2$ fields, have served to identify Monte Carlo (MC) dose cal-

FIG. 1. Annual QA percent depth ionization (PDI) data from the same machine operating at 18 MV for a 40×40 cm² field measured with the RK IC showing the effect of IC misalignment on resulting PDI data.

culuation algorithm errors,^{10,11} to resolve discrepancies in manufacturer-specified treatment head geometries,¹² and to verify physics models.⁸ These differences have also motivated studies of contaminant particle sources^{8,13–15} and the cylindrical IC EPOM.^{9,16}

The primary purpose of this work is to describe an automated procedure for IC surface identification for photon beam depth ionization measurements that is not reliant on operator's technique, skill, and patience. The motivation for this work stemmed from a desire to create reference phase space data at 6 and 18 MV to submit to the IAEA phase space database. The IAEA phase space database project aims to create a database for linear accelerators and ⁶⁰Co units by compiling properly validated existing data.¹⁷ Initially, the MC model was to be validated by comparing it with the measured depth ionization and profile data obtained during annual QA procedures. However, plotting the depth ionization results from three different acquisitions yielded the results shown in Fig. 1. In the entrance region, it is apparent that there is a discrepancy in IC positioning. Furthermore, although one measurement deviates from the others, there is no way to positively conclude that this is an erroneous data set. It is equally likely that a consistently incorrect IC positioning existed for the three measurements which coincide. In order to detect, and subsequently correct for, these sorts of systematic errors, the method presented here has been developed to determine IC location.

II. METHOD AND MATERIALS

II.A. Clinical measurements

A Scanditronix Type RK 83-05 cylindrical IC (Ref. 18) is used to acquire depth dose measurements from a Varian 21EX linac (Varian Medical Systems, Palo Alto, CA) with a $64 \times 40 \times 44$ cm³ RFA-200 water tank (IBA Dosimetry, Bartlett, TN). Details of the IC geometry obtained from the manufacturer^{18,19} indicate that the IC is 25 mm long with a 7 mm outer diameter. The steel stem is 55 mm long with an

FIG. 2. Measured PDI curve, extending into air, showing an inflection region at the air/water interface. The data were acquired with the same IC under the same conditions used to acquire the data shown in Fig. 1. The IC EPOM is shifted by 1.2 mm upstream as recommended by TG-51 ($0.6 \times r_{\text{cav}}$).

outer diameter of 4 mm. The internal air cavity has an active volume of 0.12 cm³ with a length of 10 mm and a diameter of 4 mm. The central electrode, consisting of 50% epoxy resin and 50% graphite, is 9 mm long and 1 mm in diameter. The outer wall consists of 1 mm thick PMMA with an effective thickness of 0.12 g/cm². The inner wall (outer electrode) is a 0.5 mm thick mixture of 50% epoxy resin and 50% graphite with an effective thickness of 0.07 g/cm². The insulating material used in the IC is polystyrene.

For all measurements, the EPOM is taken to be shifted 1.2 mm ($0.6 \times r_{\text{cav}}$) upstream from the center of the IC, following the recommendations of AAPM TG-51 (Ref. 5) and IAEA TRS-398,²⁰ and the water surface is located 1000 mm from the nominal source location. Using the Scanditronix/Wellhöfer OmniPro-Accept software (Version 6.5), the large step size is set to 1 mm, while the small step size is set to 0.5 mm so that ionization readings are taken every 1 mm of IC movement except in the buildup region and within ~ 2 mm of the surface in air where ionization readings are recorded in 0.5 mm intervals. The scans are performed at the medium speed setting, resulting in an IC velocity of ~ 30 mm/s. Each measurement scans from 222 mm deep in the water phantom to 50 mm upstream of the water surface to ensure observation of the ionization inflection region caused by the air-water interface. While finding the minimum scanning distance above the interface necessary to observe the inflection region was not a focus of this work, a second set of measurements not shown here indicates that scanning only 20 mm into air is sufficient to allow observation of the inflection region. Figure 2 demonstrates such an ionization inflection region, in this case acquired for an 18 MV 40×40 cm² field.

To determine the dependence of the ionization inflection region on irradiation conditions, depth ionization measurements are obtained in a single measurement session without disturbing the IC setup alignment. The IC is carefully set up per the previously referenced AAPM recommendations.

Measurements are made for the 6 and 18 MV beams at multiple field sizes, with and without a 1 mm thick Pb foil taped to the bottom of the treatment head. To ensure setup stability, the initial and final measurements are made with identical beam energy (6 MV), field size ($10 \times 10 \text{ cm}^2$), and Pb foil status (no Pb foil in the beam). Measurements taken at each beam energy with field sizes ranging from 5×5 to $40 \times 40 \text{ cm}^2$ are compared to each other in the inflection region to determine if the inflection region location depends on variations in head-scatter conditions. Similarly, measurements with and without the Pb foil are compared to determine if changes in treatment head contaminant electron fluence alter the inflection region location. Also, the 6 and 18 MV data are compared to one another to inspect potential inflection region variations with gross changes in the incident beam energy.

II.B. MC simulations

To determine the absolute water surface location with respect to the IC-produced inflection region, a series of MC simulations is performed to reproduce several of the measurement scenarios. All MC calculations conducted as part of this work are done using the EGSnrc^{21–23} codes. All calculations are performed using the same photon cutoff energy value (PCUT=0.01 MeV) and the EXACT boundary crossing algorithm, as recommended by Walters and Kawrakow.¹¹

II.B.1. BEAMnrc treatment head simulations

A BEAMnrc (Ref. 24) model of the Varian 21EX is implemented as a shared library source, allowing the single module to be directly used as a source of particles for all dose calculation user codes used in this study. A detailed description of the use of BEAMnrc shared library sources in EGSnrc user codes has been previously provided by Tonkopi *et al.*²⁵ and the efficiency of their use has been examined by Kawrakow and Walters.²⁶ The accelerator model used here is developed based on proprietary information obtained from the accelerator manufacturer. The model differs from that used to generate previously published phase space data^{27–29} in that (1) the position of the target relative to the primary collimator differs (motivated by the work of Chibani and Ma¹²), (2) a PYRAMIDS component module is added to approximate edge-of-field shielding that exists between the mirror and the jaws, and (3) an approximation has been made that the mirror lies flat perpendicular to the beam axis due to the fact that the mirror physically extends into the aforementioned shielding in the beam direction. The treatment head portion of each calculation is performed using an electron cutoff energy, ECUT, of 0.7 MeV. Directional bremsstrahlung splitting is used with a splitting number of 1000 for the 6 MV simulations and 750 for 18 MV. Range rejection is also employed with the cutoff energy set as ESAVE=2 MeV at 6 MV and ESAVE=5 MeV at 18 MV. These settings are chosen following the findings of Kawrakow *et al.*³⁰ and Kawrakow and Walters,²⁶ respectively.

To quantify the variations in contaminant electrons for the different measurement scenarios, a second set of BEAMnrc

simulations of the Varian 21EX model is performed. In contrast to the simulations previously described, the treatment head model is used here to generate phase space files rather than as a shared library source. Files are generated for both 6 and 18 MV beams and both 10×10 and $40 \times 40 \text{ cm}^2$ fields. For each of these cases, simulations are run with and without the Pb foil present in the beam path. These phase space files are then analyzed with BEAM data processor (BEAMDP).³¹ BEAMDP allows users to derive spectral and planar fluence distributions from phase space data. Using this tool, each phase space file is read for electrons passing through a 3 cm radius around the central axis at 100 cm SSD. These particles are then separated into 20 equally spaced energy bins, and the energy fluence is plotted as a function of the incident electron kinetic energy. The results of these simulations are shown in Sec. III B 3.

II.B.2. Dose calculations with IC absent

To allow quantification of the effect of the IC on the percent depth dose (PDD) and the potential variations in the EPOM as a function of depth, DOSXYZnrc simulations of a pure water phantom are also performed. For these simulations, a $64 \times 40 \times 44 \text{ cm}^3$ water phantom is utilized. Beginning from 5 cm above the water surface in air, voxel dimensions along the beam central axis are $2 \times 2 \times 0.5 \text{ cm}^3$, except within a region from 1 cm above the surface to 4 cm depth in water in which the voxel dimensions used are $2 \times 2 \times 0.1 \text{ cm}^3$. Voxel dimensions are then increased to $2 \times 2 \times 1 \text{ cm}^3$ after a depth of 10 cm within the water tank. The results of three such simulations are compared with measurements and with the results of analogous simulations with the IC present, which are described in Sec. II B 3. This comparison for the 6 MV beam and a $10 \times 10 \text{ cm}^2$ field is discussed in Sec. III B 1. The results of the same comparison conducted for both a 6 MV $40 \times 40 \text{ cm}^2$ field and an 18 MV $40 \times 40 \text{ cm}^2$ field are given in Sec. III B 2. Note that DOSXYZnrc simulations directly score the dose in water, while the simulations described in the next section effectively score the energy deposited in the air volume of the chamber. Thus, deviations between the with and without IC simulation results are not only due to electrons generated in the IC wall but also to variations in stopping powers and other IC corrections required to convert dose to air to dose in water and/or percent depth ionization (PDI) to PDD. Range rejection is also used in these calculations with the same settings as detailed in the previous section. In addition, photon splitting was employed with an n_{split} of 40. Here, ECUT is set to 0.521 MeV.

II.B.3. Dose calculations with IC present

Depth ionization calculations are done using the CAVITY and EGS_CHAMBER³² user codes to allow direct inclusion of the IC in the simulation geometry. These user codes are built on egsp, the EGSnrc C++ class library,³³ which provides a flexible geometry allowing for detailed modeling of any IC geometry. Details of the RK IC geometry are modeled to match the design provided by the manufacturer. Figure 3

FIG. 3. A view of the internal components of the RK IC model. The internal and external electrodes consist of the same epoxy/graphite mixture. The bottom region is the beginning of the steel shaft. For more information about this IC, the reader is referred to Ref. 18.

shows the internal components of the RK chamber model, created using EGS_VIEW. The EGS_CHAMBER user code is a newly developed extension of CAVITY that uses several additional variance reduction techniques including photon cross-section enhancement,³⁴ intermediate phase space storage, and correlated sampling^{35,36} to greatly enhance calculation efficiency over that which was previously achievable with CAVITY. For a more detailed discussion of the EGS_CHAMBER user code and/or the variance reduction techniques implemented within, the reader is referred to Ref. 32.

For these simulations, the “IC origin” is placed at the EPOM of the IC model, taken 1.2 mm ($0.6 \times r_{\text{cav}}$) upstream from the geometrical center of the IC, also following the recommendations of AAPM TG-51 (Ref. 5) and IAEA TRS-398.²⁰ The CAVITY simulations use a $64 \times 40 \times 44$ cm³ water phantom, while the EGS_CHAMBER simulations use a $60 \times 60 \times 2000$ cm³ phantom. This difference in phantom size is not expected to affect the results. In the EGS_CHAMBER simulations the IC is simultaneously simulated at multiple depths in the phantom by utilizing intermediate phase space storage. ECUT is set to 0.521 MeV in these simulations.

All ionization calculations are run to $\leq 1\%$ precision (one standard deviation) in water for all but a few voxels in air where “fat” electrons were scored. The most noticeable contributions from these electrons came in the EGS_CHAMBER simulations with the statistically worst voxels being in the 18 MV 40×40 cm² field simulation. The worst of these occurred 4.5 cm above the water surface where the statistical uncertainty was 8%. Five other voxels (out of 461 total) in

this particular simulation are scored with uncertainties of $> 1\%$.

II.C. Quantification of inflection region deviations and surface identification

Multiple methods could be used to determine variations in the location of the dose inflection point between various measurement field conditions or for deviations between measured and MC-simulated dose inflection locations. The aim of this portion of the study was to use a method that required as little data manipulation as possible. The method devised requires only calculation of each measurement curve’s second derivative, d^2I/dx^2 . This method works well when comparing measurements but the MC data proved too noisy for this technique to be useful. Therefore, the sum of the squared differences (SSQD) is used to quantify deviations in the dose inflection region between measurements and MC data for the various field conditions. In these comparisons, MC simulations are used as reference conditions in which the location of the water surface is known exactly with respect to the IC position. SSQD is computed using the formula,

$$\text{SSQD} = \sum_x w_x [\text{PDD}_{\text{ref}}(x) - \text{SF} \times \text{PDD}_{\text{test}}(x + \delta)]^2,$$

where ref and test refer to the reference and test conditions, SF represents a scaling factor used to account for the arbitrary normalization difference, δ represents the shift in the IC position between the ref and test depth dose conditions, and w_x represents a weighting factor taken as the inverse of the root mean squared combined variance of the ref and test data points at a given x . The variance of each measured data point is taken to be 1×10^{-10} (zero, for our purposes), while the variance of any MC-calculated data used is taken directly from the MC calculation. Results were found to be insensitive to the value of the constant variance assumed for the measurement data. Using this weighting allows the algorithm to give more importance to matching relatively well-determined data points while essentially ignoring points with larger variances. The summation is taken over depths x from 2.3 mm above the surface to 4.7 mm in water. This depth range is representative of the IC central electrode location, while the IC scans through the water surface from the point at which the IC reaches the water surface to the point at which the IC emerges fully into air. Doubling this range was shown to change any δ values by ~ 0.1 mm. SF and δ are adjusted to minimize the SSQD to determine the deviation (δ) in the entrance dose inflection region for the IC. Alternatively, the MC data sets are smoothed using a Sovitzky–Golay filter as implemented by Kawrakow³⁷ and second derivatives are then computed and compared.

FIG. 4. (a) Measurements conducted with the RK IC for the 6 MV beam at various field sizes demonstrating that changes in field size and the with/without Pb foil differences in electron contamination do not affect the inflection location. (b) The second derivative of the measured relative ionization curve is plotted as a function of depth in the water tank. The insensitivity of the curves to these changes in beam conditions indicates that the major cause of the peak in the second derivative is the IC emerging from the water tank into air. The inset shows the same data plotted over a wider range of depths.

III. RESULTS

III.A. Clinical measurements

III.A.1. Field size and electron contamination effects on the inflection region

Figure 4 compares the 6 MV measurement results for three different field sizes, with and without a Pb foil located in the beam path. Figure 5 compares the 18 MV results. The location of the peak in the second derivative is independent of the field size and the with/without Pb foil differences in electron contamination. The 0.5 mm deviations observed correspond to the smallest resolution at which these measurements were taken; therefore, these deviations are not considered meaningful. The second derivative maximum occurs at a depth of ~ 3 mm. As is explained in Sec. III C, this corresponds to the point at which the IC leading edge physically emerges from water into air.

FIG. 5. (a) Measurements conducted with the RK IC for the 18 MV beam at various field sizes demonstrating that changes in field size and the with/without Pb foil differences in electron contamination do not affect the inflection location. (b) The second derivative of the measured relative ionization curve is plotted as a function of depth in the water tank. The insensitivity of the curves to these changes in beam conditions indicates that the major cause of the peak in the second derivative is the IC emerging from the water tank into air. The inset shows the same data plotted over a wider range of depths.

III.A.2. Beam energy effects on the inflection region

A comparison of measurements taken for a 10×10 cm² field with different beam energies is shown in Fig. 6. Although the 6 and 18 MV beams produce different depth ionization curves, the shape and location of the second derivative maximum do not vary by more than 0.5 mm. Logically, the size and shape of this region will be related to the IC dimensions. Again, the second derivative maximum occurs just as the IC emerges from the water into air, which occurs at the same depth for each measurement.

III.B. MC simulations

III.B.1. Dose calculations for 10×10 cm² fields

A comparison of simulation results with and without the IC present is shown in Fig. 7. Differences in the air region are immediately observable. Since the simulation without the IC present lacks contributions from secondary electrons produced within the chamber wall, these differences are to be

FIG. 6. (a) Comparison of the effect of contaminant electrons and different photon beam energies on the location of the inflection region for a $10 \times 10 \text{ cm}^2$ field. The IC circle is intended to help guide the reader's eye to the inflection point. (b) The second derivative of the measured relative ionization curve is plotted as a function of depth in the water tank. The insensitivity of the curves to these changes in beam conditions indicates that the major cause of the peak in the second derivative is the IC emerging from the water tank into air. The inset shows the same data plotted over a wider range of depths.

expected. At the same time, excellent agreement is observed between the two simulations in water after d_{max} , confirming the $0.6 \times r_{\text{cav}}$ EPOM shift recommended by various dosimetry protocols. In the buildup region, the distance to agreement (DTA) varies, which can be attributed to a change in the EPOM shift as a function of depth, as has been shown elsewhere.^{9,16} At the surface, DTA is over 2 mm, while by 1.0 cm depth, DTA is negligible. A comparison of CAVITY simulation results with measurement is shown in Fig. 8. The choice to shift measurement to MC in this figure, rather than vice versa, is made because the surface position is user defined in the MC simulation and therefore exactly known. The same cannot be said of the surface position in the measurements. Agreement within $(2.65 \pm 0.65)\%$ or better is observed at all depths.

III.B.2. Dose calculations for $40 \times 40 \text{ cm}^2$ fields

The results of comparing measurement to MC simulation for the $40 \times 40 \text{ cm}^2$ open field case, shown for 6 MV in Fig.

FIG. 7. Comparison of simulation results between CAVITY and DOSXYZnrc. Simulation with CAVITY allows for proper modeling of the cylindrical IC geometry, while DOSXYZnrc simulation only models dose to water. The dose differences observed over the first centimeter are attributable to the lack of contribution by secondary electrons produced within the IC wall to the dose deposited within the DOSXYZnrc simulation. The TG-51 recommended EPOM shift of 1.2 mm ($0.6 \times r_{\text{cav}}$) is applied to the CAVITY results.

9 and for 18 MV in Fig. 10, exhibit poorer depth ionization agreement than the 6 MV $10 \times 10 \text{ cm}^2$ field case. What appears to be an ionization overprediction after d_{max} is caused by the curve fitting algorithm being driven to minimize differences immediately surrounding the water surface. This will be described further in Sec. III C. However, the discrepancy is believed to be caused by an underestimate of the contribution from secondary electrons in the MC beam model. It may be the case that there is more of the observed edge-of-field shielding, previously mentioned in Sec. II B 1, present in the beam path than was previously believed. Further tuning of the beam model is an ongoing project.

FIG. 8. Comparison of CAVITY simulation results with measurement for the 6 MV $10 \times 10 \text{ cm}^2$ field case. The difference in the two curves along with the MC statistical uncertainty in the point of maximum discrepancy is shown in the inset. The TG-51 recommended EPOM shift of 1.2 mm ($0.6 \times r_{\text{cav}}$) is applied to the CAVITY results. The measurement curve displayed has been shifted and scaled to the CAVITY results by the δ and SF given by the algorithm.

FIG. 9. Comparison of measurement and results of simulation with and without the IC present for the 6 MV $40 \times 40 \text{ cm}^2$ field case. The difference between EGS_CHAMBER and measurement along with the MC statistical uncertainty in the point of maximum discrepancy is shown in the inset. The TG-51 recommended EPOM shift of 1.2 mm ($0.6 \times r_{\text{cav}}$) is applied to the EGS_CHAMBER results. The measurement curve displayed has been shifted and scaled to the EGS_CHAMBER results by the δ and SF given by the algorithm.

III.B.3. BEAMnrc inspection of electron contamination with Pb foil

The variations in electron energy spectra at the phantom surface when increasing field size from 10×10 to $40 \times 40 \text{ cm}^2$, as computed via MC simulation, are shown for the 6 MV beam in Fig. 11. The analogous results for the 18 MV

FIG. 10. Comparison of measurement and results of simulations with and without the IC present for the 18 MV $40 \times 40 \text{ cm}^2$ field case. The discrepancy between measurement and both CAVITY and EGS_CHAMBER in the water region is caused by forcing the algorithm to focus on deviations near the surface with improperly modeled electron contamination from the previously mentioned edge-of-field shielding. The measured curve has been shifted to match the EGS_CHAMBER curve due to the much larger number of data points calculated with this code. The CAVITY curve is shown in the interest of comparison. The noticeably larger error bars around two of the in-air doses calculated with EGS_CHAMBER are attributable to contributions from “fat” electrons in these voxels. The TG-51 recommended EPOM shift of 1.2 mm ($0.6 \times r_{\text{cav}}$) is applied to the CAVITY and EGS_CHAMBER results. The measurement curve displayed has been shifted and scaled to the EGS_CHAMBER results by the δ and SF given by the algorithm.

FIG. 11. Examination of the influence of the Pb foil on electron energy fluence from the 6 MV beam. Energy fluence is displayed as a histogram over 20 equally spaced energy bins from 0 MeV to the maximum energy of the particles.

beam are shown in Fig. 12. While electron energy increases with beam energy, the more important result is the change in the shape of the energy fluence distribution for the $40 \times 40 \text{ cm}^2$ field at both beam energies when the Pb foil is placed in the beam. Doing so reduces the electron energy fluence distributions to appear very similar to those resulting from $10 \times 10 \text{ cm}^2$ fields. These results increase the confidence that the deviations shown in the previous section result from an improperly modeled treatment head component, most likely the aforementioned edge-of-field shielding around the mirror. Small modifications to this modeling are likely to affect electron fluence but not the relative impact of the Pb foil demonstrated by a change in shape of the electron energy fluence distribution.

FIG. 12. Examination of the influence of the Pb foil on electron energy fluence from the 18 MV beam. Energy fluence is displayed as a histogram over 20 equally spaced energy bins from 0 MeV to the maximum energy of the particles.

TABLE I. IC inflection location offsets (δ) for comparisons of measurement and MC simulation. The data taken as the baseline (ref) for the comparison are shown in the left column, while the shifted data (set) are displayed across the top.

				Measurement			
				6 MV		18 MV	
				10×10		40×40	40×40
				Pb	No Pb	No Pb	No Pb
Ref			Test	δ (mm)	δ (mm)	δ (mm)	δ (mm)
CAVITY	6 MV	10×10	No Pb	...	−0.596	...	...
EGS_CHAMBER	6 MV	10×10	Pb	−0.700	...	...	...
			No Pb	...	−0.609	...	...
		40×40	No Pb	...	...	−1.064	...
	18 MV	40×40	No Pb	...	...	...	−1.200

III.C. Measurement surface identification

The minimization algorithm described in Sec. II C was applied to the data in Figs. 8–10. For the 6 MV 10×10 cm² field case, it was determined that the measurement data required a shift of $\delta = -0.596$ mm and a scaling factor of $SF = 0.9837$ to match the measurements to the MC results, where the negative shift denotes a shift upstream toward the treatment head. This shift between measurements and simulations performed for reference conditions indicates that the true water surface was actually ~ 0.6 mm downstream of where it was defined in the measurement acquisition software, i.e., zero depth. Note that the scaling factors are measured in arbitrary units and are not pertinent to the results stated here; therefore, they are not stated for any other cases. For the 6 MV 40×40 cm² field case, the shift determined was $\delta = -1.064$ mm. For the 18 MV 40×40 cm² field case, the shift was $\delta = -1.200$ mm. The full results of these comparisons are shown in Table I. The results of the Sovitzky–Golay smoothing are shown in Fig. 13. A peak occurs at

~ 2.2 mm depth for 6 MV 10×10 cm² field simulations. Comparison with the peak shown in Fig. 4(b) at 2.8 mm for 6 MV 10×10 cm² field measurements indicates a -0.6 mm IC offset, which agrees with the offset found by the SSQD minimization algorithm. A peak at ~ 2.2 mm is also visible for 40×40 cm² field simulations with a Pb foil in the beam path. The foil reduces electron contamination, allowing the peak to become visible, while simulations at the same field size without the Pb foil in place are dominated by noise so as to obscure the peak. This noise causes the discrepancies observed in Table I as the SSQD minimization algorithm “pulls” the measured data toward agreement with the MC data. The second derivative computation method of finding IC offsets is more robust to noise than the SSQD minimization method, which has a clear dependence on electron contamination. When the IC reaches the water surface, the central electrode is at a depth at 3.5 mm. Subtracting from this the 1.2 mm recommended EPOM shift gives an expected inflection peak location of 2.3 mm. The inflection peak in the smoothed MC data at ~ 2.2 mm agrees to ~ 0.1 mm. When one subtracts the ~ 0.6 mm setup offset found in the measurements, the inflection peak in the measured data at ~ 3 mm also agrees at the ~ 0.1 mm level.

FIG. 13. The second derivatives of the MC-calculated relative ionization curves are plotted as a function of depth in the water tank. Peaks in the second derivative are visible at ~ 2.2 mm depth for 6 MV 10×10 cm² simulations (solid lines). Simulations performed for 40×40 cm² fields with a Pb foil in the beam path also exhibit peaks at this depth (dashed lines). Without the Pb foil in place, the peaks for these fields are obscured by noise caused by electron contamination (dot-dashed lines).

IV. DISCUSSION

In this work, the inflection region that exists in IC measurements at the air-water interface is used to determine the water surface location for depth ionization scanning. Measurements are performed with a variety of field conditions, demonstrating that the location of this inflection region is nearly invariant (within ~ 0.5 mm) to beam energy and reasonable variations in contaminant electrons. These measurements are fit to MC simulations to determine the absolute surface location offset δ . It is expected that this offset will be setup dependent. In this study, the δ values found are small since the IC is carefully aligned to the surface location. There is no requirement that δ be small—in fact, one could set up an IC at an arbitrary reference depth and use the through-interface scan to automatically identify the surface location. However, while it should be possible to find an offset of any amount using this procedure, the IC setup is not

unimportant. Careful IC alignment should result in a small offset, if any, found by application of the proposed method. However, if any such errors should exist, this method should make them easier to identify. Use of this method to identify the surface might heighten the focus on initial IC setup—following application of an automatic surface identification, a user should be able to visually inspect and validate the setup.

MC simulations are used as a reference for identifying the absolute surface location with respect to the IC in this work. Even without an absolute surface reference, the method of scanning through the air-water interface can improve dosimetric reproducibility. Measurements with a given IC at a given institution should agree in the ionization inflection region from one setup to the next, such as measurements made for initial accelerator commissioning and annual machine QA. Deviations in the surface ionization inflection regions should make the variability due to user setup readily observable. For measurements taken under the same field conditions, direct comparison of the depth ionization curves should reveal any shift. For measurements taken under different field conditions, the variability can be assessed by analyzing the peaks in the second derivative of ionization. Matching these data should result in a more consistent data acquisition from year to year and from physicist to physicist. In the context of this work, application of this scanning method could have avoided the deviations observed in Fig. 1. Without scanning through the air-water interface (as is the current clinical convention), there is no way to correct data offline if an error is discovered after the setup has been taken down. (In fact, such errors are likely to go undetected.) In the case that a setup error is detected, current scanning methods require a new setup and series of measurements to obtain depth ionization data. An offline correction, such as that possible using the ionization inflection region, renders this unnecessary.

The results presented in this paper only provide information sufficient to determine the surface location for a single IC, the Scanditronix RK IC. No general recommendations or prescriptions to determine the surface location from the location of the inflection region can be made having tested the method on data acquired with one type of IC. With that said, there is no reason that the method itself shouldn't be applicable to any arbitrary IC design, including parallel-plate ICs. The inflection region-matching method of surface identification should also apply for other sources of radiation although the size (and possibly the shape) of the perturbation may be radiation type dependent. In fact, Das *et al.* previously demonstrated the utility of scanning past the surface for electron beams.³⁸ The difference between their work and this work lies in the surface localization method. Due to the more linear buildup response in electron beams, Das *et al.* were able to use simple linear fitting to find the surface with one function representing the dose in air and the other representing dose in water. Given these two linear functions, valid to first approximation for electron dose near the water surface, both the surface position and dose at that depth can be found. However, this method is inadequate for photon beams due to

the greater curvature of the depth dose curve in the buildup region. The application of our method to electron beam dosimetry will be a focus of future work.

Examining the relationship between the PDI inflection region and the water surface with other IC designs is a goal of future work. Broadening the study will be made simpler by the use of other methods of surface localization such as precise measurements for each IC design and the efficient MC user code, EGS_CHAMBER. The MC simulation portion of this work has been CPU intensive and time consuming. The CAVITY simulation results shown in this work required over 4400 (40 3 GHz CPUs $\times$ 110 h/simulation) and 6000 CPU hours (150 h/simulation) for the 6 and 18 MV cases, respectively. In contrast, the 6 MV open field results obtained with EGS_CHAMBER required just under 360 CPU hours (45 3 GHz CPUs $\times$ 8 h/simulation). The measurements taken in this study were all conducted at one scanning speed starting from depth in water and ending in air, with the water tank set at a single SSD. It is possible that reversing this scanning direction, varying the speed of measurement acquisition, and/or changing the SSD may have some impact on the shape and position of the inflection region. These effects are to be studied as part of future work. Inspection of the effect of factoring out the inverse square dependence of the in-air data showed no change in the results. The ~ 0.1 mm agreement between the theoretical IC EPOM location at the water surface and that found in this study indicates the suitability of the $0.6 \times r_{\text{cav}}$ EPOM prescription in this work. Therefore, while an EPOM correction that varied as a function of depth could have been applied, this correction, if at all noticeable, would have been secondary to the issue of IC offset. The insensitivity of the measured IC-produced inflection region to field size, secondary electron contamination, and even beam energy implies that a single accurate determination of the phantom surface location with respect to the inflection region for a given IC design should be sufficient. Thus it is possible that one-time precise physical measurements for each IC model would be adequate to characterize the entrance region inflection region-surface correspondence. These measurements would most likely require some way of aligning the chamber with more precision than that of which the human eye is capable. Despite best efforts at initial alignment in this work, a -0.6 mm offset persists. Such measurements could be performed, for example, by a standard laboratory. Measurements with other IC designs will also prove useful to test the hypothesis, not tested here, that the location of the surface inflection region will be IC design dependent with the strongest dependencies being on the outer diameter of the IC wall and the wall thickness. A series of one-time MC simulations or precise measurements for each IC design could be used to quantify the inflection region location for each IC design, and from that, the surface location.

V. CONCLUSIONS

This work outlines a method for improving the accuracy and precision of initial IC setup at a water surface with the goal of improving the reproducibility and reliability of depth

ionization data. The method consists of scanning with the IC beyond the air-water interface to measure the ionization inflection region characteristic of the given IC. Scanning through the surface in this fashion allows standardization of surface definition, simplification of measurement setup procedures, reduction in user-to-user variability, and improvement of measurement reliability. This improved reliability is useful for a variety of tasks including MC model validation and treatment planning system commissioning. The measurement method provides a way to determine, and correct for, any offsets in IC setup that previously would have been impossible to quantify. Although this work used extensive MC simulations, clinical application of this surface matching procedure would require no user-specific MC calculations. The measured insensitivity of the inflection location to field size, beam energy, and electron contamination implies that reference data obtained for a given IC, either from MC simulations or precise measurements, should be sufficient to characterize the inflection region-surface location relationship.

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