Dosimetric characterization and output verification for conical brachytherapy surface applicators. Part II. High dose rate ^{192}Ir sources

Regina K. Fulkerson,^{a)} John A. Micka, and Larry A. DeWerd

Department of Medical Physics, University of Wisconsin–Madison, Madison, Wisconsin 53705

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Purpose: Historically, treatment of malignant surface lesions has been achieved with linear accelerator based electron beams or superficial x-ray beams. Recent developments in the field of brachytherapy now allow for the treatment of surface lesions with specialized conical applicators placed directly on the lesion. Applicators are available for use with high dose rate (HDR) ^{192}Ir sources, as well as electronic brachytherapy sources. Part I of this paper discussed the applicators used with electronic brachytherapy sources. Part II will discuss those used with HDR ^{192}Ir sources. Although the use of these applicators has gained in popularity, the dosimetric characteristics have not been independently verified. Additionally, there is no recognized method of output verification for quality assurance procedures with applicators like these.

Methods: This work aims to create a cohesive method of output verification that can be used to determine the dose at the treatment surface as part of a quality assurance/commissioning process for surface applicators used with HDR electronic brachytherapy sources (Part I) and ^{192}Ir sources (Part II). Air-kerma rate measurements for the ^{192}Ir sources were completed with several models of small-volume ionization chambers to obtain an air-kerma rate at the treatment surface for each applicator. Correction factors were calculated using MCNP5 and EGSnrc Monte Carlo codes in order to determine an applicator-specific absorbed dose to water at the treatment surface from the measured air-kerma rate. Additionally, relative dose measurements of the surface dose distributions and characteristic depth dose curves were completed in-phantom.

Results: Theoretical dose distributions and depth dose curves were generated for each applicator and agreed well with the measured values. A method of output verification was created that allows users to determine the applicator-specific dose to water at the treatment surface based on a measured air-kerma rate.

Conclusions: The novel output verification methods described in this work will reduce uncertainties in dose delivery for treatments with these kinds of surface applicators, ultimately improving patient care. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4862506>]

Key words: skin cancer, surface applicator, HDR

1. INTRODUCTION

Skin cancer is the most common form of cancer in the United States, with over 2×10^6 cases diagnosed each year, and an overall lifetime risk of one in five.¹ However, if detected early, nonmelanoma skin cancers can often be treated or controlled effectively with radiation therapy.^{1,2} Specialized solid conical applicators have been developed for use with ^{192}Ir high dose rate (HDR) brachytherapy sources for use in the treatment of superficial lesions. Currently, there are two manufacturers of HDR ^{192}Ir sources that offer solid conical applicators; Nucletron (Veenendaal, Netherlands) and Varian Medical Systems Inc (Palo Alto, CA). This work did not have access to the applicators manufactured by Nucletron, and instead focused on a set of applicators available from Varian. Treatments with these applicators generally include positioning the applicator flush to a lesion while the source dwells within the applicator for a predetermined amount of time to deliver the desired dose. Additional details regarding the clinical use and therapeutic principals of these types of applicators can be found in several peer-reviewed publications.^{2–6}

1.A. Source and applicator descriptions

HDR ^{192}Ir sources are well-established for the treatment of breast and prostate tumors, typically delivering a uniform dose to the tumor while limiting the dose to surrounding normal tissues.² In general, this is accomplished by a programmed transport of a HDR ^{192}Ir source from a shielded container (afterloader) via a catheter to an applicator previously placed on or within a patient. The source is stepped through one or more dwell positions within the catheter or applicator for a predetermined period of time. Treatment times at each dwell position are typically calculated with a treatment planning system.

The sources under investigation include the VariSource iX (manufactured by Alpha Omega) and the GammaMedplus iX (manufactured by MDS Nordion) from Varian. The GammaMedplus iX and VariSource iX sources are very similar geometrically (Fig. 1), although the cable material and deployment mechanism differ. Specific details for each source and deployment mechanics are discussed in the work of Palmer *et al.*⁷

FIG. 1. VariSource iX and GammaMedplus iX. (a) VariSource iX source geometry, units in mm. (b) GammaMedplus iX source geometry, units in mm. Images courtesy of Rasmussen *et al.* (Ref. 14).

Varian offers two types of applicators manufactured out of a stainless-tungsten alloy (Fig. 2) for use with the GammaMedplus iX and the VariSource iX. One applicator type positions the source parallel to the treatment surface inside a source guide tube with a nominal source to surface distance (SSD) of 12.5 mm. The other applicator positions the source perpendicular to the treatment surface with a nominal SSD of 12.5 mm. This work focused on the applicators with the source positioned parallel to the treatment surface, and the results discussed are specific to that type of applicator. Inserts ranging from 30 to 45 mm in diameter are available to collimate the field to a specific diameter. A thin (less than 1 mm) polycarbonate window attached to the distal side of each insert helps to ensure a flat contact during dose delivery. As expected, the ideal source position for the VariSource iX and GammaMedplus iX sources within the Varian surface applicators is in the center. However, due to source deployment mechanics, the source guide tube must be long enough to accommodate the overshoot observed with the VariSource iX. As a result, the programmed dwell index corresponding to the center of the applicator for the VariSource iX is 98.64 cm (rounded to 98.6 cm); leaving a 6.3 mm air gap between the most distal end of the source and the inside ter-

FIG. 2. Varian surface applicator set.

minating surface of the source guide tube. The programmed dwell index corresponding to the center of the applicator for the GammaMedplus iX is 129.16 cm (rounded to 129.2 cm); leaving a 7.4 mm air gap between the most distal end of the source and the inside terminating surface of the source guide tube. It must be noted that these dwell positions are unique to the catheter and connector used with each source and applicator combination. The manufacturer provided a 100 cm (nominal) long catheter for measurements with the VariSource iX, and a 130 cm (nominal) long catheter for measurements with the GammaMedplus iX. A schematic of the source dwell positions within each applicator is shown in Fig. 3.

1.B. Existing dosimetry protocols and output verification procedures

Part I of this paper discussed the AAPM dosimetry protocols relevant to surface brachytherapy treatments; TG-43 (Refs. 8 and 9) and TG-61,¹⁰ and will not be discussed here. Details regarding these dosimetry protocols can be found in Part I.

1.B.1. Current output verification procedures

The only peer-reviewed publication regarding quality assurance procedures for applicators used with ¹⁹²Ir sources is based on the work of Pérez-Calatayud *et al.*¹¹ for the H-type Leipzig and Valencia applicator sets available from Nucletron. No peer-reviewed recommendations have been published for the Varian surface applicators. According to Pérez-Calatayud *et al.*,¹¹ the output per unit air-kerma strength for each applicator is determined from a well chamber reading in combination with an applicator specific correspondence factor (CF). Determination of the CF was completed by placing each applicator on top of the well chamber using a specialized insert and taking a current reading. This reading, R , was then corrected for temperature and pressure, $\varphi(p, T)$, the well chamber-specific calibration coefficient, f , and then divided by the S_K of the bare source as seen in Eq. (1):^{11,12}

$$CF = \frac{R \cdot \varphi(p, T) \cdot f}{S_K}. \quad (1)$$

Pérez-Calatayud *et al.*¹¹ recommend that users complete measurements of this correspondence factor for each applicator and if their measurements agree with the published values within $\pm 5\%$, the published nominal output factors in ($\text{cGy h}^{-1} \text{U}^{-1}$) at 3 mm depth can be used for planning purposes. The output factors are based on previous work of Pérez-Calatayud *et al.*⁴ and have yet to be verified by an independent peer-reviewed publication. The technique discussed by Pérez-Calatayud *et al.* is easy to perform, however, it does not employ the well chamber in a manner for which it was designed, and can only be applied with the Standard Imaging (Middleton, WI) HDR1000 Plus well chamber and Nucletron H-type Leipzig or Valencia applicators.

FIG. 3. Schematic of source dwell positions within Varian surface applicators. (a) Varian surface applicator with VariSource iX. (b) Close-up of VariSource iX in Varian surface applicator showing dwell index. (c) Varian surface applicator with GammaMedplus iX. (d) Close-up of GammaMedplus iX in Varian surface applicator showing dwell index.

1.C. Proposed formalism

While standard dosimetry protocols exist for brachytherapy sources and low-energy external photon beams, the geometric and scatter conditions observed with the HDR ^{192}Ir and electronic brachytherapy surface applicators (discussed in Part I) do not conform to the requirements of either TG-43 or TG-61. However, since the treatment principles and energy characteristics of the HDR ^{192}Ir and Axxent applicators are similar, a single method of output verification is appropriate. The relative output measurement procedure described by Pérez-Calatayud *et al.* for the Nucletron HDR ^{192}Ir applicators may not be appropriate and only provides a con-

sistency check.¹¹ Calculations of treatment times without accounting for the presence of the applicator or treatment geometry may influence the absorbed dose. This work created a direct method of output verification that is applicable to various types of surface applicators in order to ensure an accurate dose is delivered to the patient. Details regarding the proposed formalism (output verification procedure) were discussed in Part I and are applicable for HDR ^{192}Ir source and applicators as well. Briefly, the proposed dosimetry formalism is based on an ionization chamber measurement of air-kerma rate at the applicator exit window interface, and a set of correction factors are then applied to determine an applicator-specific dose to water. In general, the absorbed dose to water is

determined as

$$K_{\text{air}} = M \cdot N_K \cdot P_{\text{elec}} \cdot P_{\text{TP}} \cdot P_{\text{cham}} \cdot P_{\text{POM}}, \quad (2)$$

$$D_{\text{water,d}} = K_{\text{air}} \cdot P_{D_w}, \quad (3)$$

where the air kerma, K_{air} is determined through: M is the measured charge reading over a collecting period; P_{elec} is the electrometer calibration coefficient; P_{TP} is the correction for ambient temperature and pressure; and N_K is an applicator-specific calibration coefficient. $P_{\text{cham}} = \frac{K_{\text{air,vol}}}{K_{\text{cham}}}$ is a chamber replacement factor, where $K_{\text{air,vol}}$ is the Monte Carlo calculated kerma to air-volume at the point of measurement and K_{cham} is the Monte Carlo calculated kerma to the chamber-volume at the point of measurement, $P_{\text{POM}} = \left(\frac{\text{SSD} + d_c}{\text{SSD}}\right)^2$ is an effective point-of-measurement correction, where d is the distance from the chamber entrance window to the center of the chamber collecting volume. The dose to water, is then determined by multiplying the air kerma, K_{air} by $P_{D_w} = \frac{D_{\text{phantom,d}}}{K_a}$, where $D_{\text{phantom,d}}$ is the Monte Carlo calculated dose to water at the depth of interest and K_a is the Monte Carlo calculated air kerma at the exit window of the applicator.

2. METHODS AND MATERIALS

2.A. Air kerma

The fundamental quantity of interest in this investigation is the air kerma or air-kerma rate at the exit window of the surface applicators. Measurements of the air-kerma rate were completed with a variety of ionization chambers including: an Exradin A3 spherical ionization chamber (Standard Imaging), and an Exradin A20 end-window parallel plate chamber (Standard Imaging). The Exradin A3 chamber is a NIST-traceable standard chamber and is available at the University of Wisconsin Accredited Dosimetry Calibration Laboratory (UWADCL). As noted in Part I, traceability is essential in order for the proposed formalism to be viable in the clinical setting. Monte Carlo simulations of various parameters associated with air kerma were completed for the Exradin A20 (and HDR ^{192}Ir applicators) to fully characterize the response and compare to measured values. The MCNP5 and EGSnrc codes were used for simulations and specific details surrounding simulation parameters (e.g., photon and electron cross-section libraries) were discussed in Part I.

2.A.1. Chamber air-kerma calibration coefficients

The Exradin A20 was calibrated for air kerma at the UWADCL, which offers AAPM-accredited NIST-traceable calibrations for various beam qualities and sources. The UW250-M (matched to the M250 NIST beam quality) and the ^{137}Cs beam quality was necessary for air-kerma calibrations coinciding with the higher energies observed with ^{192}Ir sources. Air-kerma calibration coefficients are interpolated between the UW250-M and ^{137}Cs beam qualities for HDR ^{192}Ir sources, based on the methods developed at the University of Wisconsin-Madison and currently held as an interim national standard at the UWADCL.^{13–15}

The Exradin A20 end-window parallel-plate chamber used for measurements with the HDR ^{192}Ir surface applicators was designed by Standard Imaging and is described in detail in Part I. In addition to the C552 chamber body, collector, and guard (nominal collecting volume of 0.0738 cm³), the Exradin A20 was fitted with a C552 buildup cap (BUC) (1.6 mm thick) for use with ^{192}Ir as the existing polyimide chamber window was not thick enough to provide electronic equilibrium. Chamber dimensions and material specifications were provided by the manufacturer and the effective point of measurement was assumed to be 1.8 mm back from the inside surface of the chamber entrance window based on electric field modeling (see Part I).

Air-kerma calibration coefficients were measured for the Exradin A20 with the center of the collecting volume positioned 1 meter from the source. An ^{192}Ir -specific chamber-calibration coefficient was interpolated based on the measured calibration coefficients for the UW250-M and ^{137}Cs beams, as discussed in Sec. 2.A.2. Calibration coefficients were calculated for the Exradin A20 in the same manner as described in Part I using `egs_chamber` and `DOSRZnrc`.

2.A.2. Primary measurement of air-kerma rate

A determination of the air-kerma rate at the exit window for the surface applicators used with HDR ^{192}Ir sources had to be developed. The Exradin A3 chamber provided secondary NIST-traceable measurement of the air-kerma rate with the Varian applicators and the Exradin A20 chamber was used with the clinically relevant measurement methodology. The Exradin A3 spherical ionization chamber is a 3.6 cc chamber constructed out of C552 air-equivalent plastic ($\rho = 1.76 \text{ g cm}^{-3}$). This chamber was calibrated at NIST for the ^{137}Cs and M250 beam qualities (average energy of 662 keV and 146 keV, respectively) allowing for a traceable interpolation of an ^{192}Ir (weighted average energy of 397 keV)-specific calibration coefficient. The Exradin A3 was used in previous work at the UWADCL to establish the current interim national standard for HDR ^{192}Ir sources using the seven-distance (7D) technique.^{13–15} A modified version of the seven-distance technique was used in this investigation. A comprehensive discussion of this measurement methodology can be found in Stump *et al.*¹³ and Rasmussen *et al.*,¹⁴ and a summary is provided here. The seven-distance technique uses an air-equivalent ionization chamber (Exradin A3) with an ^{192}Ir -specific air-kerma calibration coefficient to determine the air-kerma strength of a bare ^{192}Ir source. Measurements are completed at seven sequential distances starting at a nominal distance of 10 cm. Several correction factors accounting for a measurement offset from the nominal 10 cm and room-scatter are initially unknown. However, due to measurements at seven unique distances, a system of 35 nonlinear equations can be created to over-determine the magnitude of these correction factors and ultimately the air-kerma strength.

A specialized measurement apparatus is used in the seven-distance technique.¹⁴ In this investigation, the apparatus was modified to hold a surface applicator in-air in the same location the bare source would normally occupy (Fig. 4).

FIG. 4. Modified seven-distance apparatus with surface applicator.

Positioning of the applicator and chamber was achieved with two alignment lasers. Once a nominal distance of 10 cm between the applicator exit window and center of the ionization chamber was achieved, charge readings were collected with a Standard Imaging Supermax electrometer at distances ranging from 5 to 30 cm from the exit window of the surface applicator. Unlike the traditional seven-distance methodology, the source-in-applicator measurement geometry does not satisfy the initial conditions for using the system of equations as described above to determine the air-kerma strength. Instead, a power function was used to extrapolate the air-kerma rates measured at distances away from the applicator exit window back to the plane of interest. The air-kerma rate for each source and applicator combination was determined at least five times at no fewer than 10 applicator-to-chamber distances with step sizes ranging between 5 to 1 cm.

2.A.3. Measured air kerma rate with the Exradin A20 chamber

Air-kerma rate measurements at the exit window were completed for all source and applicator combinations with the Exradin A20 chamber. A combination of acrylic rods held perpendicular to one-another were used to position the Exradin A20 chamber flush to the Varian surface applicators with the C552 buildup cap (1.6 mm thick) in place during measurements. After a warm-up period of 5 min, 15 s charge readings were acquired with a Standard Imaging SuperMAX electrometer. The air-kerma rate at the surface for each source and applicator combination was calculated in the same manner as described in Part I. The source position within each applicator for all measurements with the Varian surface applicators was programmed to be 98.6 and 129.2 cm for the VariSource iX and GammaMedplus iX, respectively.

2.B. Correction factors for determination of absorbed dose to water

As discussed in Part I, the clinically relevant quantity in the proposed formalism is the dose to water at a point of interest. Correction factors accounting for the presence of the chamber during the air-kerma rate measurements (P_{cham}), in addition to a dose to water conversion from air-kerma (P_{Dw}), were determined for all source and applicator combinations using the MCNP5 and *egs_chamber* Monte Carlo codes. Applicator and chamber dimensions used in simulations were based on manufacturer-provided dimensional and material specifications. Full source models of the VariSource iX and GammaMedplus iX were used and the ^{192}Ir spectrum for each source was based on the binned energy spectra available from the ICRP.¹⁶ The collision-kerma (F6), and energy deposition (*F8) tallies were used to calculate the collision kerma and total kerma (absorbed dose), respectively, at the exit window, within the chamber collecting volume, and at points of interest away from the applicator in both air and water. Sufficient particles were run in combination with variance reduction techniques to achieve reported statistical uncertainties of less than 0.2%. Additional details regarding correction factor simulations can be found in Part I.

2.C. Dosimetric characterization

A complete dosimetric analysis of each source and applicator combination was completed using experimental techniques in addition to Monte Carlo simulations. Percentage depth-dose curves and relative dose distributions were calculated for each source and applicator combination and compared to measured values.

2.C.1. Percentage depth-dose

Percentage depth-dose curves were measured for all source and applicator combinations using the Exradin A20 chamber in a specialized water phantom. An acrylic water-proofing cap (1.6 mm thick) was manufactured by Standard Imaging for the Exradin A20 chamber. The $(31 \times 46 \times 61) \text{ cm}^3$ water phantom used for depth-dose measurements was developed by Benjamin Palmer at the UWMRRC and described in Part I. Depth dose curves were generated from the average of at least three 15 s charge readings at each depth of interest using a SuperMAX electrometer. It should be noted that chamber readings were corrected by the SSD-based inverse-square correction as discussed above in order to obtain a reading directly at the chamber/applicator interface. Monte Carlo simulations in MCNP5 of the percentage depth-dose curves for all source and applicator combinations were completed for comparison to the measured values. The applicator was positioned on the surface of a $(30 \times 30 \times 30) \text{ cm}^3$ water phantom and a cylindrical *F4 mesh tally (tally cell dimensions: $r = 0.13 \text{ cm}$, $h = 0.04 \text{ cm}$, $\theta = 2\pi$) was used to calculate the collision kerma to each tally volume. Simulations with the Varian surface applicators were completed for depths up to 50 mm.

2.C.2. Relative dose distributions

Relative surface dose distributions, profiles, and distributions at depth were measured using a combination of radiochromic films and TLDs for all source and applicator combinations. Details regarding the experimental methods for the TLD and film measurements can be found in Part I. Solid poly-methyl methacrylate (PMMA) $\rho = (1.18 \pm 0.01) \text{ g cm}^{-3}$ phantoms were constructed to hold TLD-100 microcubes and position radiochromic film for surface and at-depth measurements. Monte Carlo simulations in MCNP5 of the relative dose distributions for all source and applicator combinations were completed for comparison to measured values using a modified energy fluence (*F4) mesh tally. Additional simulations of relative surface dose distributions were completed using the *F8:p tally as the track-length estimates of collision kerma (*F4 and F6 tallies) are not appropriate near the surface or at a material boundary as charged particle equilibrium may not exist. Simulations using the *F8:p energy deposition tally explicitly account for the energy deposited from each interaction in a given tally volume for each history, offering a more accurate calculation of absorbed dose when divided by the tally cell mass. For simulations with electron transport, the above is only true if the cell is thick enough for the errors in energy loss rate to average out. Previous work of Raffi¹⁷ demonstrated discrepancies between the path-length heating tallies (*F4 and F6) and the *F8 energy-based calculation of surface dose. However, even with explicit transport of photons and electrons combined with the *F8:p tally, the complexity of interactions at interfaces may not be fully accounted for with Monte Carlo simulations and any results must be analyzed with this understanding.

For simulations of relative dose distributions with the *F8:p tally, concentric cylinders with varying radii up to $r = 3 \text{ cm}$ of height 0.01 cm were positioned at the surface of a $(30 \times 30 \times 30) \text{ cm}^3$ water phantom with each source and applicator combination placed flush to the phantom surface. The density of water, set as 0.998 g cm^{-3} per the NIST database, was used to determine each tally cell mass and applied in the calculation of absorbed dose.

2.C.2.a. Thermoluminescent dosimeters (TLDs). TLD-100 (LiF:Mg,Ti) microcubes were used for all phantom measurements using the handling and annealing procedures described in Part I. For measurements with the Varian surface applicators, the dose to the TLDs was estimated based on air-kerma rate measurements for each applicator using the Exradin A20 chamber on the same day as TLD irradiations. A target dose of 1.00 Gy was used in establishing irradiation times, and all were less than 22 s so a correction for source decay was not necessary. The intrinsic energy dependence correction factor (see Part I) applied to the TLD results for the Varian surface applicators was 0.934 (Ref. 18) A picture of the experimental setup for TLD measurements with the Varian applicators can be seen in Fig. 5.

2.C.2.b. Radiochromic film. Relative surface intensity distributions and distributions at depth were measured with HD-810 radiochromic film (Ashland Inc., Wayne, NJ). HD-810 film has a simpler construction as compared to EBT2

FIG. 5. Experimental setup for TLD irradiations with Varian surface applicators.

(used with the Axxent applicators as described in Part I) with only three layers: a clear polyester layer, an active layer, and a surface layer.¹⁹ The active layer within the HD-810 film has a much larger sensitive dose-range, from 50 to 2500 cGy and exposure times were adjusted accordingly.

Surface measurements were acquired by placing each applicator on top of a $(6 \times 6) \text{ cm}^2$ piece of film positioned in the center of a $(30 \times 30 \times 10) \text{ cm}^3$ PMMA phantom. At the request of the manufacturer, dose distributions at 1 and 3 mm depth in-phantom were acquired for the Varian surface applicators by placing material (PMMA) between the applicator and film. All films were stored and handled according to the recommendations of AAPM TG-55 report.²⁰ The Exradin A20-determined air-kerma rate was used to estimate the exposure time to deliver 60 Gy air kerma to each film.

Films were digitized at least 24 h postirradiation as recommended in TG-55 report. The HD-810 films were digitized using a Molecular Dynamics 670 nm densitometer (GE Healthcare, Pittsburgh, PA), and images were analyzed using ImageJ.

3. RESULTS

3.A. Air kerma results

As discussed, applicator and/or source-specific chamber calibration coefficients were developed for the small-volume parallel plate chambers used in air-kerma rate measurements. An ^{192}Ir -specific chamber calibration coefficient for the Exradin A20 was interpolated as described by Stump *et al.*¹³ and Rasmussen *et al.*¹⁴ and is presented in Table I.

TABLE I. Air-kerma calibration coefficients for the Exradin A20 used for interpolation of an ^{192}Ir -specific coefficient for the Varian surface applicators.

Beam quality	$N_K (\text{Gy} \cdot \text{C}^{-1})$
UW250-M	3.52×10^8
^{137}Cs	3.69×10^8
^{192}Ir	3.60×10^8

TABLE II. Air-kerma rate for the Varian surface applicators with the VariSource iX.

Applicator diameter (mm)	30	35	40	45
Chamber measured air-kerma rate (mGy · s ⁻¹)				
Exradin A3	54.6	55.1	54.5	55.1
Exradin A20	54.1	53.3	54.5	54.7
Percent difference	+1.1%	+3.5%	− 0.03%	+0.7%

Table II shows the measured air-kerma rate at the exit window for each Varian surface applicator with the VariSource iX, normalized to a reference date, as determined with the Exradin A3 chamber and the Exradin A20 chamber. Table III shows the measured air-kerma rate at the exit window for each Varian surface applicator with the GammaMedplus iX, normalized to a reference date, as determined with the Exradin A3 chamber and the Exradin A20 chamber. The values in Tables II and III represent an average of at least three trials for the Exradin A3, and at least five trials with the Exradin A20. For the VariSource iX, the Exradin A3 and Exradin A20 agreed to within 3.5% across all applicators. For the GammaMedplus iX, agreement was observed to be within 1.6% across all applicators for the two chambers. The overall agreement between the two methods of air-kerma rate determination indicates that the Exradin A20 can provide accurate results in the clinical setting when used properly.

As an additional validation of the Exradin A20, the measured air-kerma rate was compared to the Monte Carlo calculated air-kerma rate at the exit window for a given applicator. Table IV shows a comparison of the air-kerma rate at the surface from Monte Carlo simulations and measurements with the Exradin A20 chamber for the 30 mm diameter surface applicator and the GammaMedplus iX. The air-kerma rate predicted from Monte Carlo simulations was calculated using a thin cylindrical tally cell positioned flush to the exit window and collision kerma was scored. Since this Monte Carlo simulation did not explicitly account for time, the result of the simulation had to be normalized to a reference value. The air-kerma strength (AKS) of the GammaMedplus iX measured at the UWADCL was used in normalization as it is the standard quantity used in description of brachytherapy source strength. However, it must be noted that normalization to the AKS of a bare source cannot take into account any changes in the spectra observed by the ionization chamber during measurements with the surface applicators. Therefore, the comparison

TABLE III. Air-kerma rate for the Varian surface applicators with the GammaMedplus iX.

Applicator Diameter (mm)	30	35	40	45
Chamber measured air-kerma rate (mGy · s ⁻¹)				
Exradin A3	39.2	39.5	39.6	39.8
Exradin A20	39.1	38.9	38.9	39.9
Percent difference	+0.28%	+1.4%	+1.6%	− 0.14%

TABLE IV. Measured and calculated air-kerma rate at the surface of the 30 mm diameter applicator and GammaMedplus iX. Values have been normalized to a reference date.

Method	Air-kerma rate (cGy)	% difference
Measured	5.99	− 1.1%
Monte Carlo calculated	6.05	

shown in Table IV, though acceptable, is less than ideal and should only be used for observational purposes.

3.A.1. Uncertainty in air-kerma rate measurements-Varian

The uncertainties associated with measurements of the air-kerma rate were determined for each chamber used. The values presented in this section are specific to the 30 mm diameter applicator, but source specificity is maintained. A single applicator was chosen to demonstrate the parameters involved in the analysis, however the uncertainties included apply to all applicator diameters. The estimated combined uncertainty for the primary determination of the air-kerma rate with the Exradin A3 chamber includes uncertainties in the chamber calibration, the UWADCL reported electrometer calibration, the air-density correction, timing, the chamber position with respect to the center of the surface applicator exit window, the source position within the applicator, and measurement reproducibility (Tables V and VI).

The uncertainty associated with the chamber calibration coefficient was based on the reported uncertainty from the NIST calibration report for the ¹³⁷Cs beam quality. The reported uncertainty of the ¹³⁷Cs calibration point was more conservative than the reported uncertainty for the M250 calibration point. Since both beam qualities are used during the interpolation of an ¹⁹²Ir-specific air-kerma calibration coefficient and the primary uncertainties at NIST are correlated, the more conservative value was chosen for this investigation. The uncertainty in the chamber position with respect to the applicator was estimated as the influence of a 1 mm shift in the applicator to chamber distance on the air-kerma rate. The uncertainty associated with the source position within the

TABLE V. Uncertainty budget for Exradin A3 measurements of air-kerma rate for the Varian surface applicators with the VariSource iX.

Component	Type A %	Type B %
Chamber calibration		0.80
Electrometer calibration		0.10
Air density	0.1	0.1
Timing	0.51	
Chamber position relative to applicator exit window		1.2
Source position within applicator	0.8	1.4
Measurement reproducibility	0.81	
Combined uncertainty	1.1	2.0
Total uncertainty (k = 1)		2.4
Expanded uncertainty (k = 2)		4.7

TABLE VI. Uncertainty budget for Exradin A3 measurements of air-kerma rate for the Varian surface applicators with the GammaMedplus iX.

Component	Type A %	Type B %
Chamber calibration		0.80
Electrometer calibration		0.10
Air density	0.1	0.1
Timing	0.51	
Chamber position relative to applicator exit window		1.2
Source position within applicator	0.31	0.16
Measurement reproducibility	1.4	
Combined uncertainty	1.4	1.5
Total uncertainty ($k = 1$)		2.1
Expanded uncertainty ($k = 2$)		4.2

applicator was dependent on the afterloader deployment mechanics as described in Sec. 1.A. The manufacturer quotes a ± 1 mm uncertainty in the source position for any source/applicator combination. However, this broad assumption cannot be applied directly and further investigation was completed. The source position within the surface applicators is dependent on several parameters, and deviations from a programmed dwell position can be longitudinal (along the source guide tube) or transversal (perpendicular to the source long axis, corresponding to an impact on the SSD). These deviations are not predictable, and a measurement methodology was developed to characterize the uncertainties associated with source position within the applicator for each afterloader.

The uncertainty was divided into a measured Type A component, and a calculated Type B component. The Type A portion was determined as the standard deviation of the mean for the collected charge measured with a Sun Nuclear Model 100630 parallel-plate ionization chamber (Sun Nuclear Corporation, Melbourne, FL) positioned flush to the 35 mm surface applicator exit window for consecutive source deployments for the VariSource iX and GammaMedplus iX separately. This chamber was chosen for its larger volume and surface area to perform relative measurements of source-in-applicator variances. For the VariSource iX, 21 consecutive deployments to the dwell position corresponding to the center of the applicator were programmed into the afterloader, and two 15 s charge readings were acquired during each deployment. For the GammaMedplus iX, 11 consecutive deployments to the dwell position corresponding to the center of the applicator were programmed and charge was collected in the same manner. A few number of deployments was performed with the GammaMedplus iX as a reproducible chamber response was observed. The Type A component of the source position within the applicator was then calculated based on the standard deviation of the mean for the series of deployments for each source. In addition to uncertainty in source position due to source deployment mechanics, it was observed that the shape of the catheter connecting the afterloader to the applicator influenced the final source position within the surface applicators. Due to variations in patient and applicator set up in the clinical setting, the shape of the catheter cannot be predicted, and must be considered

(a)

(b)

FIG. 6. Experimental set up for the analysis of uncertainty in source position due to catheter shape. (a) Catheter with a gentle, sloping path connecting the VariSource iX afterloader and surface applicator. (b) Catheter with a tortuous path connecting the VariSource iX afterloader and surface applicator.

as a random variable in the uncertainty analysis. To estimate the Type B component of the source position uncertainty, the same experimental set up used for the consecutive source deployments was employed with a variation in the shape of the catheter. One set of charge readings for 21 consecutive deployments was obtained with a gentle, sloping shape in the catheter. A second set of charge readings for 21 consecutive deployments was obtained with a stronger radius of curvature in the catheter. Figure 6 shows the two catheter shapes used with the VariSource iX. This experimental method was repeated for the GammaMedplus iX afterloader.

The estimated combined uncertainty for the air-kerma rate measurements made with the Exradin A20 chamber are displayed in Tables VII and VIII.

Parameters included in the uncertainty budget were the UWADCL reported chamber calibration, the UWADCL reported electrometer calibration, the air-density correction, timing, the chamber position with respect to the center of the surface applicator exit window, the source position within the

TABLE VII. Uncertainty budget for Exradin A20 measurements of air-kerma rate for the Varian surface applicators with the VariSource iX.

Component	Type A %	Type B %
Chamber calibration		0.80
Electrometer calibration		0.10
Air density	0.10	0.10
Timing	0.51	
Chamber positioning on applicator exit window		0.04
Source position within applicator	0.8	1.4
Effective point-of-measurement correction		2.7
Measurement reproducibility	1.4	
Combined uncertainty	1.6	3.1
Total uncertainty (k = 1)		3.5
Expanded uncertainty (k = 2)		7.1

applicator, the effective point of measurement correction, and measurement reproducibility. Similar to measurements with the Exradin A3 chamber, the uncertainty associated with the chamber calibration coefficient was the value reported by the UWADCL for the ^{137}Cs beam quality. The uncertainty associated with timing was calculated using the timer error equation described in Attix.²¹ The chamber position uncertainty describes the associated uncertainty with positioning the chamber in the center of the applicator, flush to the exit window. This value was determined with Monte Carlo simulations of the influence of a 0.4 mm displacement of the chamber position on the exit window on the resulting air-kerma rate. The source position uncertainty was calculated in the same manner as described above for the air-kerma rate measurements with the Exradin A3 chamber. The largest contributor to the uncertainty budget for measurements with the Exradin A20 was in the estimation of the effective point of measurement. For the Exradin A20, this value was based on the influence of a 0.7 mm shift in the effective point of measurement on the resulting air-kerma rate. The uncertainty associated with measurement reproducibility was calculated as the percent standard deviation of the mean. This particular analysis was applied universally to all determinations of repetitive measurement uncertainty.

TABLE VIII. Uncertainty budget for Exradin A20 measurements of air-kerma rate for the Varian surface applicators with the GammaMedplus iX.

Component	Type A %	Type B %
Chamber calibration		0.8
Electrometer calibration		0.10
Air density	0.10	0.10
Timing	0.51	
Chamber positioning on applicator exit window		0.04
Source position within applicator	0.31	0.16
Effective point-of-measurement correction		2.7
Measurement reproducibility	2.0	
Combined uncertainty	2.0	2.8
Total uncertainty (k = 1)		3.5
ADCL reported expanded uncertainty (k = 2)		7.0

TABLE IX. Calculated P_{cham} for the Exradin A20 and the surface applicators of interest. These values were derived from MCNP5 simulations.

Varian surface applicators with VariSource iX	
Diameter (mm)	P_{cham}
30	0.987
35	0.987
40	0.987
45	0.987
Varian surface applicators with GammaMedplus iX	
Applicator diameter (mm)	P_{cham}
30	0.987
35	0.987
40	0.987
45	0.987

3.B. Correction factors

As discussed in Part I, Monte Carlo techniques were applied to calculate the necessary correction factors for the proposed dosimetry formalism. The associated uncertainties with each factor are discussed in Sec. 4.A.

3.B.1. Chamber replacement factor

Table IX shows the chamber replacement factor, P_{cham} for the various source and applicator combinations as calculated with MCNP5. The values calculated for the applicators used with the VariSource iX and the GammaMedplus iX are comparable due to the similarities in source construction, as well as the fact that the same applicator set is used with both sources.

3.B.2. Dose to water conversion factor

As observed with the chamber replacement factor, the dose to water conversion values are virtually identical for the VariSource iX and GammaMedplus iX (Table X). The uncertainties associated with each chamber correction factor are discussed in Sec. 4.A.

3.C. Dosimetric characterization

3.C.1. Percentage depth dose in water

Percentage depth dose curves were generated for each source and applicator combination. Results for the Varian surface applicators were normalized to a depth of 5 mm, as requested by the manufacturer. Figure 7 shows the measured and calculated depth dose curves for the Varian applicators with the VariSource iX, and Fig. 8 shows the measured and calculated depth dose curves for the Varian applicators with the GammaMedplus iX. The depth dose curves for all of the Varian applicators were similar in shape and magnitude for both sources, and excellent agreement was observed between the measured and calculated values. The largest discrepancy was observed with the 35 mm diameter applicator

TABLE X. Calculated P_{D_w} values for the surface applicators of interest.

P_{D_w} : Varian surface applicators with VariSource iX									
Diameter (mm)	Depth (mm)								
	0	0.1	0.5	1.0	1.5	2.0	2.5	3.0	5.0
30	1.134	1.143	1.068	0.993	0.925	0.864	0.808	0.757	0.596
35	1.135	1.143	1.069	0.994	0.926	0.864	0.809	0.758	0.596
40	1.135	1.144	1.069	0.994	0.926	0.865	0.809	0.759	0.597
45	1.136	1.144	1.069	0.994	0.926	0.865	0.810	0.759	0.597
P_{D_w} : Varian surface applicators with GammaMedplus iX									
Diameter (mm)	Depth (mm)								
	0	0.1	0.5	1.0	1.5	2.0	2.5	3.0	5.0
30	1.134	1.143	1.067	0.992	0.924	0.863	0.807	0.756	0.594
35	1.135	1.143	1.068	0.993	0.925	0.863	0.808	0.757	0.595
40	1.135	1.144	1.068	0.993	0.925	0.864	0.808	0.757	0.595
45	1.136	1.145	1.069	0.994	0.926	0.864	0.809	0.758	0.596

FIG. 7. Percentage depth dose curves in water for the Varian surface applicators and VariSource iX.

FIG. 8. Percentage depth dose curves in water for the Varian surface applicators and GammaMedplus iX.

with the GammaMedplus iX; with a 11% difference at a depth of 27.6 mm. This difference is likely due to a slight offset in chamber positioning, and/or uncertainty in the source position, as all other measured and calculated depth dose values agreed to within 1.5% on average.

3.C.2. Relative dose distributions

Relative surface distributions and distributions at depth were created for each source and applicator combination. Results were normalized to the maximum value in the center of the applicator. Figure 9 shows the dose profiles generated for the Varian surface applicators with the VariSource iX. Similar results were observed with the Varian surface applicators with the GammaMedplus iX. In general, there was good agreement between the measured and calculated dose profiles. The error bars on each TLD data point represent the standard deviation across all TLDs used for measurements at that location. A full uncertainty analysis regarding TLD measurements and Monte Carlo parameters is discussed in Sec. 4.A. A rigorous uncer-

tainty analysis for the film measurements was not performed as it was only used for relative measurements.

The ring-type artifact observed at the terminating edge of each insert with the film and Monte Carlo results varied in magnitude, with the film results showing a larger artifact than the Monte Carlo predicted values. This is most likely due to an increase in uncertainty at the outermost edges of the applicator/insert with the Monte Carlo simulations. The ring-type artifact is not discernible with the TLD measurements due to volume averaging over the finite size of the detector.

Figure 10 shows the relative profiles at the surface and at depth as calculated with Monte Carlo and measured with film in a solid phantom. While this study was completed for all applicator diameters with the VariSource iX and the GammaMedplus iX, only data for the 30 mm diameter applicator is presented. The generalized patterns observed with the 30 mm diameter applicator were consistent across all applicator diameters. The profiles in Fig. 10 were normalized to the center at a depth of 3 mm. The film-generated surface profile was slightly wider than the

FIG. 9. Relative surface dose profiles for the Varian Surface applicators and VariSource iX.

Monte Carlo calculated profile (16.9 mm and 14.2 mm at the 120% level for the film and MC, respectively). This discrepancy decreases with depth, and excellent agreement is observed at a depth of 3 mm. The profiles at depth also demonstrate a lack of the ring-type artifact observed at the surface. This indicates that the surface artifact is most likely due to secondary electrons produced at the edges of the cone that deposit all their energy within a depth of 1 mm.

Figure 11 shows the relative surface distributions generated using ImageJ and MATLAB from the HD810 film measurements for the Varian surface applicators and VariSource iX. As with the previous relative measurements, this study was completed for all source and applicator combinations with similar results across all. Results were subtracted for background and normalized to the maximum value in the center. The distributions are very similar for both sources, exhibiting a central region of high intensity with a rapid fall-off to the edges. The ring-type artifact is apparent for all applicators, the magnitude of which averages 30% of the maximum central value. As each image was analyzed separately, the color scale may differ between images.

4. DISCUSSION

4.A. Proposed dosimetry formalism dose comparison

Although there is no published peer-reviewed dosimetric methodology available for direct comparison to the results of this investigation, several relevant observations can still be made. All dose values in this section have been normalized to a reference date for a direct comparison. Tables XI and XII show a comparison of the dose to water at the surface as determined through the proposed formalism and the dose to water from the center TLDs from the phantom measurements. Very similar dose values were measured for each applicator independent of the source. The slight variation in source geometry between the VariSource iX and the GammaMedplus iX was not expected to greatly influence the doses measured with either detector. Agreement to within 4.5% was observed between the predicted dose to water at the surface based on the measurement of air-kerma with the Exradin A20, and the dose to water at the surface as measured with the TLDs. This agreement falls within the expected uncertainties discussed below.

FIG. 10. Dose profiles at the surface and at depth in a solid phantom for the VariSource iX and 30 mm diameter applicator. Dashed lines represent film results, solid lines represent Monte Carlo results.

As discussed, TG-43 is the standard dosimetry protocol for interstitial treatments with brachytherapy sources. However, the scatter and geometry conditions observed with the surface applicators do not meet the criteria discussed in TG-43.

TABLE XI. Comparison of dose to water at the surface determined through the proposed formalism and TLD measurements for the GammaMedplus iX.

Diameter (mm)	$D_{w, \text{TLD}}$ cGy	$D_{w, \text{chamber}}$ cGy	% difference
30	109.0	111.9	−2.6%
35	107.0	112.0	−4.5%
40	111.1	112.1	−0.8%
45	107.9	112.1	−3.7%

Table XIII shows a comparison of the TG-43 calculated doses to water for the GammaMedplus iX at a variety of distances along the transverse axis of the source and the corresponding dose to water as determined with the proposed formalism for each source within the surface applicators. The values for the dose-rate constant and radial dose function applied to obtain the TG-43 dose to water at a distance of 12.5 mm from the transverse axis of the source were based on the online database available from the Carleton Laboratory for Radiotherapy Physics (Ottawa, Ontario, Canada).^{9,22} A distance of 12.5 mm in water was chosen to correspond with the nominal SSD of the surface applicators. The 2D-anisotropy function is defined to be unity along the transverse axis and no additional

FIG. 11. Relative surface distributions for the Varian Surface applicators and VariSource iX.

TABLE XII. Comparison of dose to water at the surface determined through the proposed formalism and TLD measurements for the VariSource iX.

Diameter (mm)	$D_{w, \text{TLD}}$ cGy	$D_{w, \text{chamber}}$ cGy	% difference
30	107.2	111.9	-4.2%
35	107.0	112.0	-4.5%
40	112.3	112.1	+0.1%
45	108.2	112.1	-3.5%

anisotropy factors were applied. An average percent difference is presented in Table XIII as TG-43 cannot account for the collimation of the field as observed with the applicators. It is clear that TG-43 overestimates the dose when compared to the predicted values of the proposed formalism. This is expected as TG-43 only allows for a calculation of dose in a homogeneous water environment.

A relative comparison of the dose determined using the proposed formalism and that determined with Monte Carlo simulations and measurements was made. Figure 12 shows a comparison of the depth dose in water for the 30 mm diameter applicator and GammaMedplus iX source, normalized to a depth of 5 mm. The values for the water tank measurements and Monte Carlo simulations are the same as shown in Fig. 8. The values determined using the proposed formalism were based on the measured air-kerma rate and the appropriate P_{cham} and P_{D_w} correction factors. The proposed formalism agrees well with the measured and calculated values. A slight offset can be observed at distances very close to the exit window of the applicator, and is possibly due to the extrapolation methods applied to obtain the dose at the surface for the P_{D_w} correction factor.

4.A.1. Varian-specific estimated uncertainty for dose to water determination

The estimated uncertainty budget for the dose to water determination for the Varian surface applicators using the proposed formalism is shown in Table XIV. The uncertainties included are those associated with the calculated correction factors (P_{cham} and P_{D_w}) added in quadrature with the uncertainty in the air-kerma rate determination. The Monte Carlo components used to estimate the uncertainties associated with the correction factors include the simulation geometry, energy spectrum, atomic cross sections, and tally statistics. The uncertainty in the simulation geometry was estimated by observing the influence of a perturbation of the tally cell volume and shape in water. The tally region for the P_{D_w} correction factor

TABLE XIII. Comparison of dose to water as determined with the proposed formalism and TG-43.

Diameter (mm)	$D_{w, \text{chamber}}$ cGy	$D_{w, \text{TG-43}}$ cGy	Average % difference
30	111.9		
35	112.0		
40	112.1	188.7	-40.6%
45	112.1		

Depth dose in water comparison

30 mm diameter applicator, GammaMedplus iX

FIG. 12. Comparison of percent depth dose in water for the 30 mm diameter Varian surface applicator and GammaMedplus iX.

was a cylinder of radius = 0.2616 cm and a height = 0.01 cm. This nominal value was perturbed by changing the height to 0.05 cm and the radius to 0.2193 cm (separately) and the resulting effect on the P_{D_w} factor was quantified. The uncertainty in the energy spectrum and cross section was calculated as discussed in Part I. The overall uncertainty is within acceptable limits when the additional uncertainties associated with clinical procedures as discussed in Nag *et al.* are considered.²³

A separate analysis of the uncertainties associated with the absolute dose to water determination from the TLD measurements was completed. The estimated uncertainty budget for TLD measurements with the Varian surface applicators is shown Table XV. The parameters associated with the TLD readings from measurements with the applicators included TLD reproducibility, positioning, irradiation time, PMT linearity, reader stability, and the source position within the applicator. The TLD reproducibility was estimated as the percent standard deviation of the mean of all TLDs used to determine the dose in the center of the applicator (corresponding to a location in the PMMA phantom of $r = 0$ cm and $j = 0^\circ$). The uncertainty of the TLD position within each well of the phantom was estimated as a triangular distribution

TABLE XIV. Estimated uncertainty in the dose to water determination of the proposed formalism for the Varian surface applicators.

Component	Type A %	Type B %
<i>Monte Carlo uncertainties</i>		
Geometry		0.16
Energy spectrum		0.01
Atomic cross-sections		0.16
Tally statistics	0.42	
Combined uncertainty	0.42	0.17
Type A and Type B combined		0.46
Uncertainty in air-kerma rate		3.5
Total uncertainty ($k = 1$)		3.6
Expanded uncertainty ($k = 2$)		7.2

TABLE XV. Estimated uncertainty for the TLD measured dose to water for the Varian applicators and VariSource iX.

Component	Type A %	Type B %
<i>R-corrected TLD reading</i>		
TLD reproducibility	0.78	
TLD positioning		0.05
TLD irradiation time	0.51	
PMT linearity correction		0.1
Reader stability		0.2
Source position	0.8	1.4
<i>N-calibration coefficient (measured)</i>		
TLD reproducibility	0.25	
Air-kerma rate determination		0.8
TLD positioning		0.0
TLD irradiation time		0.01
Field uniformity		0.1
PMT linearity correction		0.1
Reader stability		0.2
<i>Phantom correction (¹⁹²Ir component)</i>		
MC statistical uncertainty	0.23	
Photon spectrum		0.04
Cross section		0.01
Geometry		0.16
<i>Phantom correction (⁶⁰Co component)</i>		
MC statistical uncertainty	0.07	
Photon spectrum		0.04
Cross section		0.01
Energy dependence correction	0.77	1.6
Combined uncertainty	1.5	2.30
Total uncertainty (k = 1)		2.7
Expanded uncertainty (k = 2)		5.5

based on the machining tolerance of the mill used during fabrication. The TLD irradiation time is based on the timer error determined with the Attix formalism as discussed previously. The PMT linearity correction uncertainty accounts for the possible nonlinear response of the PMT in the reader and is based on previous work at the UWMRRC by Bartol *et al.*²⁴ Similarly, the reader stability has been characterized and assigned a value in the University of Wisconsin Radiation Calibration Laboratory (UWRCL) Quality Manual.²⁵ The uncertainty of the source position within the applicator was applied in the same manner as described previously. As this uncertainty is source-specific, the values in Table XV are specific to the TLD measurements with the VariSource iX. The VariSource iX was chosen as it provided a more conservative estimate of the uncertainties as compared to the source position within the applicator for the GammaMedplus iX.

The next component of the TLD uncertainties stems from the calibration coefficient, which provides a conversion from the light output in nC to a dose. The parameters included for this component include the TLD reproducibility, the air-kerma rate determination, the TLD positioning and irradiation time, the field uniformity, the PMT linearity, and reader stability. The TLD reproducibility was analyzed as the percent standard deviation of the TLDs used for calibration. The uncertainty of the air-kerma rate determination describes the

methods used in measuring the air-kerma rate from the ⁶⁰Co source at the UWADCL and is based on previous work at the UWMRRC.²⁶ The TLD positioning, irradiation time, PMT linearity and reader stability uncertainties were analyzed with the same values as discussed above. The field uniformity uncertainty is based on the UWRCL Quality Manual.²⁷

The next two components of the TLD uncertainties are associated with the Monte Carlo calculated dose to water correction factor. Separate simulations for the various components of the correction were completed and the uncertainties for each stemmed from the reported simulation statistics, the photon spectrum, the cross sections, and the simulation geometry. For the simulations using ¹⁹²Ir, the uncertainties associated with the spectrum and cross section were based on the work of Raffi *et al.*²⁸ The uncertainty in the simulation geometry was estimated by perturbing the thickness of the source guide tube and observing the influence on the Monte Carlo calculated dose to TLD. Similar perturbation studies were carried out concerning the opening angle of the cone and the thickness of the polycarbonate window yielding similar results. For simulations using ⁶⁰Co, the values for the photon spectrum and cross section uncertainties were based on previous work including Pike¹⁸ and Kennedy *et al.*²⁶ The final parameter included in the uncertainty budget is an estimation of the uncertainty in determination of the intrinsic energy dependence correction factor as reported through the studies of Raffi¹⁷ and Pike.¹⁸ Although the values in Table XV are specific to the VariSource iX, those observed with the GammaMedplus iX were nearly identical.

5. CONCLUSIONS

This investigation has produced a clinically relevant and practical method of measuring the dose from a variety of surface applicators used with high dose-rate brachytherapy sources using a small-volume end-window parallel plate ionization chamber. The proposed dosimetry formalism is centered on a measurement of the air-kerma rate at the exit window of the surface applicator and correction factors are applied to obtain a dose to water. The correction factors introduced in the proposed formalism were calculated using Monte Carlo simulations and account for the perturbation of the radiation field due the presence of the chamber and the conversion of air kerma to a dose to water at a given depth of interest. TLDs, film, and Monte Carlo simulations were used to characterize the relative dose distributions including surface dose profiles, dose distributions, and percent depth dose curves in water.

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- ^{a)} Author to whom correspondence should be addressed. Electronic mail: rmkenned@gmail.com
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