Air-kerma strength determination of a new directional ^{103}Pd source

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Purpose: A new directional ^{103}Pd planar source array called a CivaSheet™ has been developed by CivaTech Oncology, Inc., for potential use in low-dose-rate (LDR) brachytherapy treatments. The array consists of multiple individual polymer capsules called CivaDots, containing ^{103}Pd and a gold shield that attenuates the radiation on one side, thus defining a hot and cold side. This novel source requires new methods to establish a source strength metric. The presence of gold material in such close proximity to the active ^{103}Pd region causes the source spectrum to be significantly different than the energy spectra of seeds normally used in LDR brachytherapy treatments. In this investigation, the authors perform air-kerma strength (S_K) measurements, develop new correction factors for these measurements based on an experimentally verified energy spectrum, and test the robustness of transferring S_K to a well-type ionization chamber.

Methods: S_K measurements were performed with the variable-aperture free-air chamber (VAFAC) at the University of Wisconsin Medical Radiation Research Center. Subsequent measurements were then performed in a well-type ionization chamber. To realize the quantity S_K from a directional source with gold material present, new methods and correction factors were considered. Updated correction factors were calculated using the MCNP6 Monte Carlo code in order to determine S_K with the presence of gold fluorescent energy lines. In addition to S_K measurements, a low-energy high-purity germanium (HPGe) detector was used to experimentally verify the calculated spectrum, a sodium iodide (NaI) scintillating counter was used to verify the azimuthal and polar anisotropy, and a well-type ionization chamber was used to test the feasibility of disseminating S_K values for a directional source within a cylindrically symmetric measurement volume.

Results: The UW VAFAC was successfully used to measure the S_K of four CivaDots with reproducibilities within 0.3%. Monte Carlo methods were used to calculate the UW VAFAC correction factors and the calculated spectrum emitted from a CivaDot was experimentally verified with HPGe detector measurements. The well-type ionization chamber showed minimal variation in response (<1.5%) as a function of source positioning angle, indicating that an American Association of Physicists in Medicine (AAPM) Accredited Dosimetry Calibration Laboratory calibrated well chamber would be a suitable device to transfer an S_K -based calibration to a clinical user. S_K per well-chamber ionization current ratios were consistent among the four dots measured. Additionally, the measurements and predictions of anisotropy show uniform emission within the solid angle of the VAFAC, which demonstrates the robustness of the S_K measurement approach.

Conclusions: This characterization of a new ^{103}Pd directional brachytherapy source helps to establish calibration methods that could ultimately be used in the well-established AAPM Task Group 43 formalism. Monte Carlo methods accurately predict the changes in the energy spectrum caused by the fluorescent x-rays produced in the gold shield. © 2015 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4935409>]

Key words: brachytherapy, dosimetry, directional sources, TG43, air-kerma strength

1. INTRODUCTION

CivaTech Oncology, Inc. (Durham, NC) has developed a novel directional ^{103}Pd planar source array known as the CivaSheet™ for use in low-dose-rate (LDR) brachytherapy treatments. The CivaSheet is an array of discrete ^{103}Pd source elements referred to here as CivaDots (or dots). Each dot is comprised of a small cylindrical ^{103}Pd source encased in a polymer and shielded on one side. The intent is for the array of dots to be scalable depending on the size of the treatment area by cutting a standard-sized sheet into a customized size at

the time of treatment. The maximum CivaSheet size will have a width and length of $5 \times 15 \text{ cm}^2$ with 8 mm spacing between the center of each dot, yielding 108 dots in 18 rows of 6. Each dot will be oriented such that the shields are all on the same side of the CivaSheet yielding a “hot” and “cold” side.

More traditional brachytherapy source arrays have been used in interstitial implants, especially for the treatment of nonsmall-cell lung cancer^{1,2} and have been shown to result in significant improvements in local recurrence.^{3,4} Two examples of these source arrays are ^{125}I seeds embedded into a vicryl mesh⁵ and ^{131}Cs BrachyMesh arrays⁶ commercially produced

by IsoRay Medical, Inc. (Richland, WA). The use of planar and directional sources such as the CivaSheet in brachytherapy has been developed on the basis that it can potentially lead to increased normal tissue sparing and an improved therapeutic ratio in contrast to traditional LDR sources. Lin *et al.*⁷ and Chaswal *et al.*⁸ studied directional interstitial sources and found significant reduction in dose to normal tissue for breast and prostate brachytherapy, respectively. In principle, the CivaSheet could be used on numerous tumor types including early stage nonsmall-cell lung cancer, head and neck cancer, colorectal cancer, ocular melanoma, soft tissue sarcoma, and skin cancer.

The individual elements of traditional LDR ^{125}I and ^{131}Cs brachytherapy source arrays^{5,6} are calibrated according to the methods of the American Association of Physicists in Medicine (AAPM) Task Group No. 43 Report⁹ and its associated Update of AAPM Task Group No. 43 Report (TG-43U1).^{10,11} The U.S. standard for determination of the S_K of low-energy LDR brachytherapy sources is the National Institute of Standards and Technology wide-angle free-air chamber (NIST WAFAC).¹² For the traditional source arrays, the S_K is measured for each source individually and then dose to water calculations are performed by using published TG-43U1 tabulated data. Since multiple sources are sutured into an array, the superposition of all the elements of an array is calculated and tabulated in the form of a dose lookup table or nomogram.¹ However, in the case of the CivaSheet and more specifically its dots, their directional nature precludes the direct application of the Task Group 43 protocol. It is the goal of this work to determine the S_K of a CivaDot by securing the dot on a stationary holder and calculating new correction factors based on an experimentally verified energy spectrum, and to test the transfer of the calibration to a well-type ionization chamber.

The University of Wisconsin variable-aperture free-air chamber (UW VAFAC) is a large-volume free-air chamber much like the NIST WAFAC, but with five available aperture sizes instead of a single fixed aperture.¹³ The UW VAFAC has been used for the primary calibration of coiled ^{103}Pd sources¹⁴ and more recently for the calibration of a new 1 cm long ^{103}Pd source.¹⁵ Since no primary calibration has previously been performed on directional ^{103}Pd LDR brachytherapy sources, our goal was to determine the S_K of individual dots of a CivaSheet with the UW VAFAC using appropriately calculated correction factors for the dots. The correction factors account for the materials present in the UW VAFAC setup and also the unique energy spectrum emitted from the dots. The correction factors were calculated either analytically or by using Monte Carlo techniques. With the presence of gold in the vicinity of the active ^{103}Pd volume, the spectrum will be different than that of traditional sources due to the production of fluorescent x-rays in the gold shield. To evaluate and benchmark the Monte Carlo calculated spectra, measurements were performed with a low-energy high-purity germanium (HPGe) detector and compared with the spectrum predicted by the Monte Carlo simulations.

It is assumed that a more directionally uniform emission from a brachytherapy source makes an S_K measurement less

sensitive to setup position and makes the comparison with UW VAFAC measurements with different apertures and the NIST WAFAC more robust. Since the dots are anisotropic by nature, the in-air anisotropy was measured with a NaI scintillating detector around one of the CivaDots. The purpose of performing anisotropy measurements was to benchmark the Monte Carlo calculations as well as investigate the effect of using different apertures for the S_K measurements. This is an important detail for this work since the UW VAFAC Aperture No. 3 was used, which is larger than the NIST WAFAC aperture.

For traditional LDR sources, S_K is disseminated to clinical users via a well-type ionization chamber calibrated at an AAPM Accredited Dosimetry Calibration Laboratory (ADCL). Consistency in the ratio of the S_K to well chamber reading over multiple measurements must be observed for this transfer to be robust. For this directional source investigation, a custom insert was used to secure a single dot in the center of a well-type ionization chamber. Measurements at several insert rotation angles were performed to test the symmetry of the custom holder and directional source. A low angular dependence means that the transfer of S_K to a well-type ionization chamber would be practical and feasible for dissemination to clinical users.

2. METHODS AND MATERIALS

2.A. The CivaDots

The CivaSheet is a variable-sized ^{103}Pd source array with discrete source elements called CivaDots (or dots). Details of the dimensions, material compositions, material densities, and distribution of radioactive ^{103}Pd material within the CivaDots were obtained from CivaTech Oncology, Inc. The dots consist of a cylindrically shaped region that contains ^{103}Pd , a low-Z organic polymer encapsulation, a gold disk-shaped shield, and a bioabsorbable membrane encasing all of the dots in an array. Figure 1 illustrates the configuration of an example CivaSheet consisting of nine dots, and Fig. 2 shows a schematic diagram of an individual dot. Realistically, CivaSheets will contain many more than nine dots, but the smaller size is shown here

FIG. 1. A schematic of a sample CivaSheet™ array of nine dots. The dots are all oriented such that the shields are on the same side and are embedded in a flat bioabsorbable membrane. Fenestrations manufactured in the material are shown as white circles. Please note that the illustration is not to scale.

FIG. 2. A schematic showing the basic components of a CivaDot in a cross-sectional view. The schematic illustrates the region of ^{103}Pd and the gold layer for shielding. The cold direction corresponds to the side of the dot with the gold shield. Please note that the illustration is not to scale.

for illustration purposes. For this project, we will refer to the sides of the dot as either being hot or cold. The cold side is the side with the gold shield. Fenestrations are manufactured in the bioabsorbable membrane material for surgical purposes. The maximum size of the CivaSheet is $5 \times 15 \text{ cm}^2$ and it can be trimmed in the treatment room to the size of the area to be treated.

The dot is a cylindrical organic polymer capsule with an outer diameter of 1.265 mm and thickness of 0.490 mm. Centered in the capsule along the cylindrical axis is a thin ^{103}Pd region with a diameter of 0.20 mm and a height of 0.080 mm. The bottom of this region is 0.365 mm from the hot side of the source (with the bioabsorbable membrane material present) and is defined as the reference plane (or zero distance) for measurements of S_K . The intersection of the cylindrical axis of the dot and the reference plane is defined as the origin for the measurements and Monte Carlo simulations. Secured above the palladium region is a thin cylindrical layer of gold intended to attenuate the source on the cold side. This gold layer has an outer diameter of 0.925 mm and a thickness of 0.050 mm and is centered on the cylindrical axis of the dot at a distance of 0.1 mm from the reference plane. The entire dot is enclosed between two bioabsorbable 0.125 mm uniformly thick membranes.

For the S_K measurements performed in this work, single dots were manufactured within a bioabsorbable membrane approximately $3 \times 3 \text{ cm}^2$ in size. The bioabsorbable membrane, although not the same length and width as a clinical sheet, is the same thickness and material as would be used for the larger sized CivaSheet. The purpose of encasing the single dots in the bioabsorbable membrane, as opposed to measuring the bare dot, is to mimic the clinical treatment conditions and to consider the dot and surrounding membrane material together as a singular source for dosimetry calculations.

2.B. UW VAFAC

The UW VAFAC is a large-volume free-air chamber that can be used for S_K measurements of brachytherapy sources with photon energies up to 70 keV.^{13–15} The sensitive collecting volume of the UW VAFAC is 40 cm in diameter and is positioned 20 cm downstream from the plane of the collimating aperture stand. The source is secured behind a shielded enclosure and the aperture stand is mounted at a fixed distance of 30 cm from the source. Figure 3 shows a schematic of the UW VAFAC with the CivaDot in its measurement position. The VAFAC operates as an air ionization chamber and utilizes the change in the ionization current as a function of plate separation to determine the air-kerma produced at a well-defined distance from the source.

The UW VAFAC has five sizes of interchangeable brass apertures, which are held in place 30 cm from the source. For all measurements in this work, Aperture No. 3 (VA3) was used. This aperture collimates the radiation emitted from the dot into a cone with a half angle of 10.39° . This is slightly larger than the NIST WAFAC aperture with a half angle of 7.6° but is still within the uniform emission angle of the dot, as discussed later. The aperture collimates the primary beam and penumbra of the source such that they are completely

FIG. 3. Schematic of the measurement setup with a CivaDot in its fixed measurement position with the UW VAFAC. Please note that the illustration is not to scale.

contained within the sensitive collecting volume of the UW VAFAC. The use of VA3 for an S_K measurement provides an improved signal-to-noise ratio.

To be consistent with the TG-43U1 (Ref. 11) definition of S_K , a high-purity 0.086 mm aluminum filter is positioned in the beam path to remove photons with energies less than 5 keV. This is similar to the NIST WAFAC measurement protocol.¹² The measurement procedure involves recording multiple ionization current measurements with electrode separations ranging from 5 to 15 cm, as described in detail elsewhere.^{13,14} Linear regression techniques are used to fit the measurement data and determine a corrected ionization current per unit distance of electrode separation $d(kI)/ds$. This value is used to determine the S_K of the source as shown in Eq. (1). For each source, the measurement was repeated without repositioning to calculate the measurement repeatability. An average S_K of all measurements was taken to be the final S_K of the source.

The UW VAFAC determines S_K by using the following equation:¹³

$$S_K = \left(\overline{W}/e\right)_{\text{air}} \frac{d^2}{\rho_{\text{air}} A_{\text{eff}} (1 - g_{\text{air}})} \cdot \frac{d(kI)}{ds} \cdot \prod_i k_i, \quad (1)$$

where $\left(\overline{W}/e\right)_{\text{air}} = 33.97$ eV (Ref. 16) is the mean energy required to produce an ion pair in dry air, $\rho_{\text{air}} = 1.196$ kg m⁻³ is the density of air in the chamber at 22 °C and 101.325 kPa, A_{eff} is the effective area of the beam collimating aperture, g_{air} is the fraction of the initial electron energy lost by radiative processes in air ($g_{\text{air}} \approx 0$ for energies less than 100 keV), $d(kI)/ds$ is the increment of corrected ionization current (background and leakage subtracted, corrected to reference temperature and pressure) per increment of the electrode separation (s), and k_i 's are source-specific correction factors applied to the measured currents.

2.C. Source holder and alignment

To accommodate the unique dot design, a new source holder was developed to hold the dots during measurements. The source needs to be secured while minimizing the surrounding scatter media. It was also important for the cylindrical axis of the dot to be aligned with the cylindrical axis of the UW VAFAC. To this end, a goal-post-shaped PMMA holder with an outer width of 8.5 cm and an inner width of 5 cm in the horizontal direction was used to suspend the dot in air. A schematic of a dot in place for measurements is shown in Fig. 4. A thin piece of adhesive tape was then used to attach the cold side of the dot to the sides of the frame. Regarding dot orientation, the hot side was always set to face the collecting volume and the front face of the outer bioabsorbable membrane was used for initial alignment. A side laser was used to align the front face of the membrane at 30 cm from the plane of the defining aperture. An offset of 0.365 mm was then introduced by a precision translation stage so as to place the source origin (described in Sec. 2.A) in the same location as the VAFAC origin. The source is not rotated during the measurement since it is directionally dependent

FIG. 4. Schematic of a CivaDot in its PMMA window-frame holder for UW VAFAC measurements. Please note that the illustration is not to scale.

by design and there is no need to average over the azimuthal anisotropy as with traditional LDR sources.

2.D. CivaDot ^{103}Pd loading

As described in Sec. 2.A, the dots have an active palladium region which contains ^{103}Pd material of variable loading. The amount of ^{103}Pd that is loaded into a given dot is based on the prescription dose and the specific activity of ^{103}Pd . With different ^{103}Pd loading schemes, the energy spectrum emerging from the source will change due to changes in the absorption of fluorescence L -shell x-rays originating in the gold shield. This variation is small, but requires attention with regard to the correction factors for S_K measurements. In this work, all the Monte Carlo simulations assumed the ^{103}Pd region to be uniformly filled with 50% palladium material and 50% epoxy by mass, with the net density of $\rho = 1.9987$ g cm⁻³.

2.E. Correction factor calculations

A number of correction factors are applied to the UW VAFAC measurements to determine S_K . These corrections were calculated either analytically or with Monte Carlo techniques. The transport code MCNP6 (Ref. 17) with the updated photon cross section library mcplib12 was used to model the dots. The mcplib12 (Ref. 17) cross section library contains updated atomic cross sections for low-energy photons, important for this work since the presence of the gold shield results in the generation of L -shell fluorescence x-rays. Previous cross section libraries combined L -shell interactions into a single x-ray energy, so the mcplib12 cross section library and MCNP6 Monte Carlo code are an ideal choice for this application.

The dot geometry was modeled according to design information provided by CivaTech Oncology, Inc. The ^{103}Pd source spectrum used in this work was obtained from the National Nuclear Data Center online NUDAT 2.6 database.¹⁸

A detailed description of the correction factors was given by Seltzer *et al.*¹² and Culbertson *et al.*¹³ For this work,

the correction factors were calculated using MCNP6 following the same methodology as applied to ^{103}Pd coiled sources by Paxton *et al.*¹⁴ CivaDot correction factors are similar to those of conventional ^{103}Pd sources for the geometric-based and reference condition-based factors such as the corrections for decay, temperature, pressure, humidity, and ion recombination. However, the rest of the factors are dependent on the energy spectrum and must be recalculated for this work. A complete MCNP6 model of the UW VAFAC was used to determine each of the correction factors that required Monte Carlo simulations.

2.F. Well-type ionization chamber measurements

S_K is typically measured by clinical users via a well-type ionization chamber with a calibration coefficient from an ADCL. These chambers are cylindrically symmetric and hold the source along the cylindrical axis during a measurement. With a directional source such as a CivaDot, the transfer of any source strength metric requires a uniform response of the chamber regardless of dot orientation. To verify this, a custom source holder was manufactured by Standard Imaging, Inc. (Middleton, WI) to hold a single dot. A hinged PMMA frame-style holder was designed to suspend the dot in air along the cylindrical axis of a well chamber at the axial point of maximum response. The frame is snapped shut to hold the bioabsorbable membrane with the dot. The insert was designed to fit in a commercially available Standard Imaging HDR1000 Plus well-type ionization chamber. To test the response of the system, a series of measurements were made with different source holder rotations and compared to a measurement at a reference position. A schematic of the newly designed source holder is shown in Fig. 5.

In addition to the variation in response with angle, the ratio of S_K to well-chamber ionization current S_K/I (also known as the ionization chamber calibration coefficient) was determined for four different CivaDots and compared to the

FIG. 5. Diagram of the CivaDot holder for use with a Standard Imaging HDR1000 Plus well-type ionization chamber. The CivaDot shown in the figure is held by securing the surrounding bioabsorbable membrane in a hinged frame holder. Please note that the illustration is not to scale.

mean. For an S_K calibration to effectively be transferred to a well-type ionization chamber, the S_K/I should remain consistent from source to source as expected for traditional LDR brachytherapy sources.

2.G. Spectral study

As discussed in Sec. 2.E, the existence of the gold shield in such close proximity to the ^{103}Pd region creates a spectrum that is different than that of traditional LDR ^{103}Pd brachytherapy seeds. This spectrum can be calculated with Monte Carlo methods if the correct cross section libraries are used. For this work, a Canberra Industries Inc. (Meriden, CT) low-energy HPGe spectrometer was used to verify the calculated spectrum by measuring the pulse height distribution with the CivaDot secured in air with the same holder that was used for UW VAFAC measurements described in Sec. 2.C. The HPGe detector was positioned on the dot cylindrical axis to capture the spectrum in the same emission direction as the UW VAFAC. At the beginning of the measurement session, a detector energy calibration was performed using ^{109}Cd , ^{55}Fe , and ^{241}Am sources, all of which have photon emissions in the <60 keV energy range.

To clearly identify the spectral effects of the gold shield, a custom unshielded CivaDot was manufactured by CivaTech Oncology, Inc., and used to compare with a shielded dot. The spectra of the shielded and the unshielded dot were measured with the HPGe detector system sequentially in the same measurement session, thus having the same detector energy calibration. Pulse-height distributions with acquisition times >20 h were recorded for both the dot with gold shield and dot without gold shield. The difference spectrum was used to analyze the spectral effects introduced by the gold shield by using a subtractive technique. This technique was performed by calculating the difference between the normalized spectra of the shielded and the unshielded dots for each channel.

2.H. CivaDot anisotropy measurements

To realize the S_K of a source with the UW VAFAC with a relatively large aperture (half angle of 10.39°), it is important that the source emission is approximately uniform within the measurement aperture. Although not all traditional sources emit uniformly within the aperture used by the NIST WAFAC, it is a desirable feature to enable future comparisons with multiple large-volume free-air chambers. To quantify the anisotropy of the CivaDot within the UW VAFAC measurement aperture, a NaI detector manufactured by Ludlum Measurement, Inc. (Sweetwater, TX) was used. This NaI detector was mounted at a distance of 95 cm from the source and the CivaDot was rotated in discrete steps while acquiring counts with the NaI detector. Measurements with an acquisition time of 60 s were performed at each angle in 1° increments. The measured data were compared with Monte Carlo calculations and an analysis was performed in the central measurement region for estimating any azimuthal anisotropy due to source construction.

FIG. 6. Results of the HPGe spectra measurements of a typical CivaDot (shown in black) and a specially constructed dot without the gold shield (shown in gray) normalized to maximum count.

3. RESULTS

3.A. Spectral measurements and calculations

The pure ^{103}Pd source spectrum is assumed to be accurate since it is based on the well-established NUDAT 2.6 database.¹⁸ Therefore, the focus of this spectral study was on the gold fluorescent x-ray radiation due to the presence of the gold shield. The results of the CivaDot spectral measurements and calculations are plotted in Figs. 6 and 7. Figure 6 shows two measured spectra, one from a specially constructed dot without the gold shield and one from a typical CivaDot. The spectra were both normalized to peak heights of the most abundant 20.2 keV ^{103}Pd emission line. Figure 7 shows the difference of the two spectra to highlight the impact of the gold shield. One can see the difference in the spectra in the range of 8–15 keV where the dot without gold does not emit L -shell fluorescence x-rays. In addition to the difference spectrum shown in black, the MCNP6 Monte Carlo-predicted difference spectrum is shown in gray. It is clear that the measured difference spectrum is consistent with the calculated difference spectrum in the area of interest (8–15 keV). This agreement is important since spectra calculated with previous versions of MCNP (version 5) had a mismatch with the measured spectra in this energy range. The results of this investigation verify the adequate simulation of the discrete L -shell gold fluorescent x-rays originating in the gold shield using MCNP6 with the updated photon cross section library (mcplib12). Please note that the measured data were not corrected with a detailed detector response function.

3.B. UW VAFAC correction factors

The correction factors for a CivaDot were determined through either analytical methods or Monte Carlo simulations and are tabulated in Table I. All Monte Carlo corrections were determined with the MCNP6 code using updated cross section libraries. The statistical standard deviation of the simulations for all the corrections was less than 0.1% (1σ). It is apparent that the corrections for attenuation between the source and the

FIG. 7. Shown in black are the results of the HPGe differential measurements for a typical CivaDot and a special dot without the gold shield. Also plotted in gray is the MCNP6 Monte Carlo calculated difference spectrum for the CivaDots.

free-air chamber including k_{fil} , $k_{\text{att-el}}$, $k_{\text{att-SA}}$, $k_{\text{att-VAFAC}}$ are all different for a CivaDot than those for a pure ^{103}Pd source. This is due to the lower average energy of the emitted spectrum which includes the gold fluorescence x-rays. Specifically, the correction for the aluminum filter attenuation, k_{fil} , is 1.1404 for the CivaDot and only 1.0773 for a pure ^{103}Pd source. A larger correction in itself is not a source of additional uncertainty as long as the spectrum used for the calculation is constant and well known. To account for the potential variability in ^{103}Pd loading and the possible effects on k_{fil} , an additional uncertainty has been added as addressed in Sec. 3.F.

3.C. NaI detector anisotropy measurements

Figure 8 shows the angular fluence distribution measured with a NaI detector and predicted with MCNP6 Monte Carlo simulations around a CivaDot. The zero degree angle is defined with the dot in its S_K measurement position (cylindrical axis of the dot in alignment with the cylindrical axis of the UW VAFAC) for both the measurements and Monte Carlo simulations. Statistical uncertainties at individual measurement points are generally 1% or less. Changes with angle are significant due to the presence of the gold shield and the directional nature of the source. There is also a noticeable dip in the fluence around 90° and 270° due to attenuation in the bioabsorbable membranes.

In the angle defined by the UW VAFAC Aperture No. 3 (half angle of 10.39°), the measured and simulated fluences at each discrete angle (intervals of 1°) are equal to the distribution on the central axis to within the uncertainty in both the measured and simulated results. This means that a comparison can be made with other apertures smaller than UW VAFAC Aperture No. 3 without having to correct for any anisotropy within the aperture-defined collecting volume.

TABLE I. Correction factors used for VAFAC measurements of a CivaDot with a 30 cm source-to-aperture distance and UW Aperture No. 3. Original correction factors were calculated by Culberson *et al.* Ref. 13.

Correction factor	Description	Original ^{103}Pd	CivaDot
k_{dec}	Correction to the reference date, $T_{1/2}(d)$	$T_{1/2} = 16.99d$	
k_{TP}	Air temperature and pressure correction	$[(273.15 + T)/(273.15 + T_{\text{ref}})] \cdot [P_{\text{ref}}/P]^a$	
k_{sat}	Ion-recombination correction	1.000	
k_{hum}	Humidity correction	0.9979	
k_{stem}	Source-holder correction	1.0000	1.0000
k_{pen}	Aperture-penetration correction	1.0000	0.9986
k_{fil}	Attenuation in aluminum filter	1.0773	1.1404
$k_{\text{att-el}}$	Attenuation through the entrance electrode	1.0019	1.0033
$k_{\text{att-VAFAC}}$	Attenuation in air from the aperture to the VAFAC	1.0179	1.0232
$k_{\text{att-SA}}$	Attenuation in air from the source to the aperture	1.0269	1.0388
$k_{\text{int-sca}}$	Internal photon scatter correction	0.9911	0.9919
$k_{\text{ext-sca}}$	External photon scatter correction	0.9909	0.9929
k_{invsq}	Inverse-square correction for aperture	1.0167	1.0167
$\prod k_{\text{corr}}$	Product of correction factors	$1.1241(k_{\text{dec}} \cdot k_{\text{TP}})$	$1.2135(k_{\text{dec}} \cdot k_{\text{TP}})$

^a $T_{\text{ref}} = 22^\circ\text{C}$ and $P_{\text{ref}} = 101.33\text{ kPa}$.

3.D. CivaDot S_K measurements

Air-kerma strength measurements determined with the UW VAFAC for a batch of four CivaDots are given in Table II. Also shown are the reproducibility values (the type A component of the uncertainty analysis) for each measurement as well as the relative combined standard uncertainty. Reproducibility is defined as the standard deviation of the mean of the determined S_K values from each measurement. Since the source orientation was not changed between measurements, reproducibility is effectively equal to the repeatability of the measurement and is an indicator of measurement precision. The measurement precision ($<0.3\%$) is more than acceptable for a primary measurement of LDR brachytherapy source

strength since it is lower than the 0.75% stated uncertainty of the UW VAFAC with a coverage factor of $k = 1$.¹³ In addition to individual dot measurement precision, the similarity in S_K as shown in the second column of Table II demonstrates a consistent value of S_K within a batch with a deviation from the average of $<1.5\%$.

3.E. Well-type ionization chamber system symmetry

Measurements of ionization current were performed with the custom-made dot holder inside a Standard Imaging HDR1000 Plus well-type ionization chamber at four cardinal angles. The results of the well-type ionization chamber measurements are plotted in Fig. 9 and show a variation in response of the system of $<1.5\%$ for all four sources in the batch at all four cardinal angles. The results were normalized to an average of the five readings for each dot and indexed with a permanent mark on the holder and chamber. The results indicate that the chamber and holder system exhibit a variation in response with angle consistent from dot to dot within a batch, indicating a small amount of cylindrical asymmetry. This variation could be from the chamber or the source holder. For implementation of the well chamber as

FIG. 8. In-air fluence data from a CivaDot measured with a NaI detector are plotted in black. The MCNP6-predicted fluence distribution is plotted in gray. Notice the significant asymmetry due to the presence of the gold shield.

TABLE II. Air-kerma strength results for four CivaDots from a single batch. Measurements were performed with the UW VAFAC Aperture No. 3, which corresponds to a half angle of 10.39° . The relative standard uncertainty ($k = 1$) takes into account the repeatability as well as generalized type A and type B uncertainties of the VAFAC. S_K/I is the ratio of air-kerma strength to well-chamber ionization current and is normalized to the average of all the dots.

Source ID	UW VAFAC $S_K (U)$	Reproducibility (%)	Relative standard uncertainty (%)	Normalized S_K/I
1	2.275	0.23	1.80	0.997
2	2.325	0.17	1.79	1.011
3	2.294	0.08	1.79	1.000
4	2.272	0.25	1.80	0.991

Fig. 9. Results of the change in ionization current with a CivaDot secured in a custom holder within a Standard Imaging HDR1000 Plus well-type ionization chamber as a function of angle. The values for a given dot are normalized to the average of the five readings for each dot. The fifth reading was acquired at the initial zero degree orientation to evaluate repeatability.

the presumed best method to disseminate S_K to clinical users, an average of readings at multiple holder rotations should be used to avoid introducing a systematic bias at a single angle. Even if the source of asymmetry were to be identified and remedied, making four measurements at the cardinal angles is a reasonable expectation for any ADCL or clinical user.

Measurements of ionization current with the Standard Imaging HDR1000 Plus well chamber were averaged over the four angular measurements and compared with the S_K values determined with the UW VAFAC. The S_K/I values listed in Table II are normalized to the average of all sources. The overall uncertainty ($k = 2$) reported by the UWADCL for calibrations of conventional seeds using the HDR1000 Plus well chamber is about 2.4%. The variation in S_K/I is <1.2%, which demonstrates sufficiently low variation for the eventual transfer of S_K to a clinical user, given the uncertainties in S_K and well chamber measurements.

3.F. Uncertainty

The combined (types A and B) relative standard uncertainty associated with UW VAFAC measurements of ^{103}Pd sources is given by Culberson *et al.*¹³ to be $\sqrt{\sigma_{\text{rep}}^2 + 0.75^2}$, where σ_{rep} is the reproducibility of the measurement. A coverage factor of 2 ($k = 2$) is then applied to this value to arrive at the relative expanded uncertainty.

Unique to this work is the uncertainty due to the variation in palladium loading within the CivaDot. This uncertainty affects the correction factors since the energy spectrum is subject to slight variations with changes in palladium loading. To capture this uncertainty, the approach taken for this work was to calculate the correction factors for both a 20% ^{103}Pd loading and an 80% ^{103}Pd loading by mass. This corresponds to physically possible values (since there must be some amount of palladium in the region and it cannot be fully loaded) and

represents a range of correction factor values that could be expected.

CivaDot spectra with 20% and 80% palladium loading were both simulated separately using MCNP6 with the UW VAFAC setup. Correction factors were then calculated for both cases using the same methodology as applied for the calculation of correction factors shown in Table I (50% palladium loading). When all correction factors are multiplied together, a net correction factor is used to predict the variation as a function of palladium loading. The change in net correction factor between 20% and 50% loading is +2.38% and between 80% and 50% loading is -2.81%. Using a conservative approach and assuming a rectangular/uniform distribution for palladium loading with bounds of $\pm 2.81\%$, the estimated type B (Ref. 19) uncertainty associated with CivaDot S_K correction factors is 1.62% and can be added in quadrature to yield a relative standard uncertainty for the UW VAFAC with CivaDots to be $\sqrt{\sigma_{\text{rep}}^2 + 0.75^2 + 1.62^2}\%$. For example, if we consider the maximum value of σ_{rep} from Table II, then the relative standard uncertainty for that measurement is 1.80%.

4. DISCUSSION

The UW VAFAC was successfully used to measure the S_K of four CivaDots. Instead of rotating the source, the dots were fixed in a PMMA holder. Precise alignment to the dot origin was achieved by using a side laser and indexing from the front face of the bioabsorbable membrane with a precision translation stage. The setup is robust and minimizes scatter (compared to a solid-backed holder) by suspending the dot in air at the UW VAFAC origin. The precision of the measurements performed in this work was high, yielding low overall uncertainties for the determination of S_K . The emitted energy spectrum was measured and compared with Monte Carlo simulations. Both results show a significant presence of low-energy L -shell fluorescent x-ray radiation originating in the gold shield within the dot. By using the updated photon cross section libraries, individual L -shell lines were accurately predicted and simulated.

A new well-type ionization chamber fixture was designed and manufactured specifically for CivaDot source strength measurement in a Standard Imaging HDR1000 Plus well chamber. The variation in the system response as a function of source and holder rotation was <1.5% and was found to be consistent among four dots in a batch.

We have shown that the effect of the palladium loading within the dot is a significant additional source of uncertainty for S_K determination. However, the effect on the dose distribution in water is unknown and is an area of future work.

5. CONCLUSION

Successful S_K measurements of CivaDots indicated that air-kerma strength is a good source strength metric to use with the AAPM TG-43U1 Report.¹⁰ Repeated measurements

with the UW VAFAC indicate that a NIST WAFAC-based standard is both feasible and practical as a source strength metric for a CivaDot. Correction factors were recalculated due to the difference in energy spectra between the CivaDot and the bare ^{103}Pd sources used for current correction factor calculations. The corrections are larger since the energy spectrum contains more low-energy emission lines from the presence of the gold shield in near proximity to the ^{103}Pd region. This is an important characteristic to consider when determining dosimetry parameters according to the AAPM TG-43U1 Report.¹⁰

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