Assessment of the setup dependence of detector response functions for mega-voltage linear accelerators

Christopher Fox^{a)}

Sun Nuclear Inc., 425-A Pineda Court, Melbourne, Florida 32940 and Department of Radiation Oncology, University of Florida, P.O. Box 100385, Gainesville, Florida 32610-0385

Tom Simon

NRE, 202 Nuclear Science Building, University of Florida, P.O. Box 118300, Gainesville, Florida 32611-8300 and Sun Nuclear Inc., 425-A Pineda Court, Melbourne, Florida 32940

Bill Simon

Sun Nuclear Inc., 425-A Pineda Court, Melbourne, Florida 32940

James F. Dempsey

ViewRay Inc., 2 Thermo Fisher Way, Oakwood Village, Ohio 44146

Darren Kahler, Jatinder R. Palta, Chihray Liu, and Guanghua Yan

Department of Radiation Oncology, University of Florida, P.O. Box 100385, Gainesville, Florida 32610-0385

(Received 16 March 2009; revised 7 December 2009; accepted for publication 8 December 2009; published 7 January 2010)

Purpose: Accurate modeling of beam profiles is important for precise treatment planning dosimetry. Calculated beam profiles need to precisely replicate profiles measured during machine commissioning. Finite detector size introduces perturbations into the measured profiles, which, in turn, impact the resulting modeled profiles. The authors investigate a method for extracting the unperturbed beam profiles from those measured during linear accelerator commissioning.

Methods: In-plane and cross-plane data were collected for an Elekta Synergy linac at 6 MV using ionization chambers of volume 0.01, 0.04, 0.13, and 0.65 cm³ and a diode of surface area 0.64 mm². The detectors were orientated with the stem perpendicular to the beam and pointing away from the gantry. Profiles were measured for a 10 × 10 cm² field at depths ranging from 0.8 to 25.0 cm and SSDs from 90 to 110 cm. Shaping parameters of a Gaussian response function were obtained relative to the Edge detector. The Gaussian function was deconvolved from the measured ionization chamber data. The Edge detector profile was taken as an approximation to the true profile, to which deconvolved data were compared. Data were also collected with CC13 and Edge detectors for additional fields and energies on an Elekta Synergy, Varian Trilogy, and Siemens Oncor linear accelerator and response functions obtained. Response functions were compared as a function of depth, SSD, and detector scan direction. Variations in the shaping parameter were introduced and the effect on the resulting deconvolution profiles assessed.

Results: Up to 10% setup dependence in the Gaussian shaping parameter occurred, for each detector for a particular plane. This translated to less than a ±0.7 mm variation in the 80%–20% penumbral width. For large volume ionization chambers such as the FC65 Farmer type, where the cavity length to diameter ratio is far from 1, the scan direction produced up to a 40% difference in the shaping parameter between in-plane and cross-plane measurements. This is primarily due to the directional difference in penumbral width measured by the FC65 chamber, which can more than double in profiles obtained with the detector stem parallel compared to perpendicular to the scan direction. For the more symmetric CC13 chamber the variation was only 3% between in-plane and cross-plane measurements.

Conclusions: The authors have shown that the detector response varies with detector type, depth, SSD, and detector scan direction. In-plane vs cross-plane scanning can require calculation of a direction dependent response function. The effect of a 10% overall variation in the response function, for an ionization chamber, translates to a small deviation in the penumbra from that of the Edge detector measured profile when deconvolved. Due to the uncertainties introduced by deconvolution the Edge detector would be preferable in obtaining an approximation of the true profile, particularly for field sizes where the energy dependence of the diode can be neglected. However, an averaged response function could be utilized to provide a good approximation of the true profile for large ionization chambers and for larger fields for which diode detectors are not recommended. © 2010 American Association of Physicists in Medicine.

[DOI: [10.1118/1.3284529](https://doi.org/10.1118/1.3284529)]

I. INTRODUCTION

The high degree of target volume conformity achievable with modern external beam treatment techniques requires an accurate knowledge of high dose gradient regions for treatment planning.^{1,2} Beam modeling in a treatment planning system (TPS) requires a combination of profile and depth dose information to replicate the accelerator beam characteristics for calculation of the treatment dose.² The accuracy of measurement of the penumbral region, therefore, translates directly into treatment planning accuracy. Ionization chambers are commonly used for data collection during acceptance testing and commissioning of linear accelerators.²⁻⁴ However, it is well understood that ionization chambers inherently influence measurements in the penumbral region, distorting the “true” beam profile. The degree of this effect is heavily dependent on the chamber design and tends to increase as a function of chamber volume.^{5,6} Consequently, without consideration of the chamber volume effect such distortions will be included in the TPS beam modeling. Chamber motion, detector noise, setup, and mechanical accuracy can also introduce measurement uncertainty. These effects can be limited somewhat through careful setup and selection of equipment. The effect of the chamber volume is more difficult to remove.

Several investigators have proposed measurement techniques and corrections to approximate the profile acquired by an infinitesimally small ionization chamber with good signal to noise ratio, by accounting for the smearing effect introduced by large volume ionization chambers, such as the 0.13 cm³ CC13 (Wellhöfer-Scanditronix, Bartlett, TN). These measurement techniques have included, but are not limited to, the use of small volume ionization chambers,⁷ solid state detectors,⁸ polymer gels,⁶ and profile deconvolution.⁹ Although all of these methods address the effect of chamber size, each introduces additional issues for data collection and assessment. For example, small ionization chambers increase the measurement resolution at the expense of signal to noise ratio. Solid state detectors can be manufactured in submillimeter sizes for improved resolution of the penumbral region. However, they are known to over respond to low energy radiation.¹⁰ Gels are single use devices and can be expensive, which makes them undesirable for routine measurements. The zero volume ionization chamber profile can be obtained from large volume chamber measurements by one of two methods: (1) Extrapolation, where profiles are obtained with ionization chambers of varying radii, and then extrapolated to a zero radius chamber. This method requires the availability of a large collection of ionization chambers, and the data sets would need to be extrapolated for each field size used in the commissioning process. Previous work by Pappas⁶ measured the penumbral width using polymer gels down to 0.3 mm in width. It was found that a gel detector size ~ 0.5 mm diameter is sufficient to resolve the unperturbed beam penumbra. (2) Deconvolution of the detector response from the measured profiles has been

shown to be an effective technique in obtaining the unperturbed, or true, profile. However, the detector response has to be known in advance.^{9,11}

It has been shown by Yan *et al.*¹² that for a particular choice of ionization chamber, a single detector response function can be used in the deconvolution process over a range of field sizes. Additionally, the benefits of profile deconvolution in TPS commissioning models applied to IMRT were investigated using the MAPCHECK (Sun Nuclear Inc. Melbourne, FL) 2D array for patient QA. It was found that the passing rate for a 2%/2 mm criteria improved from 82% to 97% for IMRT QA when comparing the beam delivered to the 2D array to a 2D dose plane from a beam model commissioned with a 6 mm diameter ionization chamber and one commissioned with deconvolved data. Thus, deconvolving the detector response out of the data is desirable for improved beam modeling and IMRT QA. The purpose of this work is to assess the deconvolution method using several routinely employed detection mechanisms over a variety common setup scenarios.

II. METHODS AND MATERIALS

II.A. Beam data collection

All profile scans were obtained with a Wellhöfer 3D blue phantom and processed with the OMNIPRO-ACCEPT 6.5 software (Wellhöfer-Scanditronix, Bartlett, TN). Data were collected for 10 $\times$ 10 cm² fields, defined at 100 cm from the source, on an Elekta Synergy linac at a nominal energy of 6 MV. The collection depth ranged from 0.8 to 25 cm and source-to-surface distance (SSD) from 90 to 110 cm. Additional data were obtained at 90 cm SSD for the same range of depths for 4 $\times$ 4 and 10 $\times$ 10 cm² fields at 10 and 18 MV nominal energies. Data for a Varian Trilogy linac were obtained at 6 MV for fields of 4 $\times$ 4 and 10 $\times$ 10 cm². Siemens Oncor data were acquired for 5 $\times$ 5 and 11 $\times$ 11 cm² fields at 6 MV. Profiles were scanned in continuous mode at intervals of 0.04 cm. Data were collected using Wellhöfer ionization chambers of radii 1, 2, 3, and 3.1 mm and respective lengths 3.6, 3.6, 5.8, and 23.1 mm corresponding to models CC01, CC04, CC13, and FC65. Additional profiles were obtained with an Edge (Sun Nuclear Inc., Melbourne, FL) diode detector of surface area of 0.64 mm². A telescopic water phantom table (Wellhöfer-Scanditronix, Bartlett, TN) allowed for the variation in SSD between 90 and 110 cm. All fields were defined at isocenter. The water depth was sufficient for profile measurements between 0.8 and 25 cm depths. The location of the point of measurement of each chamber was offset toward the radiation source by $0.6r_{\text{cav}}$ to account for the effective point of measurement of the ionization chamber. The diode detector did not require an offset. The detectors were set in a horizontal orientation. Profiles were obtained in the cross-plane and in-plane directions. Data were smoothed, centered, normalized to the center of the profile, and made symmetric-using the mean of the left and right sides of the profile before being exported in ASCII format for analysis. The smoothing was performed using a median function which steps through the profile in user defined steps calcu-

lating the median for a user defined region. The step size and region were chosen so as to reduce fluctuations in the profiles due to noise while maintaining the shape in the penumbral region. The change in the penumbra associated with changing depth and SSD was investigated and the influence on the kernel shape was compared for each detector.

The effects of the detector response were removed (deconvolved) from each chamber profile. The Edge detector was taken as an approximation of the true profile to which all deconvolved profiles were compared. Pappas⁶ showed that a gel detector of <0.5 mm diameter was sufficient to produce the true profile and that a pin point chamber, of diameter 2 mm, overestimates the penumbra of a 5 mm beam by 0.72 mm. The Edge detector of width 0.8 mm was deemed sufficiently small to provide an approximation of the true profile. Finally, the detector profiles were deconvolved using the averaged Gaussian shaping parameter obtained from all depth and SSD combinations for each detector. Additionally, a 10% variation in the shaping parameter was introduced and the deconvolution was repeated. The effect on the resulting deconvolved profile was investigated.

II.B. Profile deconvolution and beam profile fitting

The method of profile deconvolution used in this work has been previously discussed¹² and is based on the work by Garcia-Vicente *et al.*,⁹ and will be discussed briefly here. The measured profile data can be described using the convolution of the detector response function and the true profile from

$$P_m(x) = \int P_t(r)K(x-r)dr, \quad (1)$$

where P_t and P_m are the true profile and measured profiles, respectively, and $K(x-r)$ is a Gaussian detector response or kernel function of the form

$$K(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma^2}\right), \quad (2)$$

where σ is the Gaussian shaping parameter. Discrete deconvolution can be applied directly to the measured data using Fourier transforms as

$$P_t = F^{-1}\left(\frac{F[P_m(x)]}{F[K(x)]}\right). \quad (3)$$

F and F^{-1} represent the Fourier transform and inverse Fourier transforms, respectively. However, discrete deconvolution can propagate noise and uncertainties in the measured data, which can affect the final result. The influence of such errors can be limited by application of filters in the process; however, the quality of the result is dependent on the cut off frequency chosen in the filtering and must be applied on a case by case basis. The analytical approach proposed by Garcia-Vicente⁹ limits the influence of data noise through an analytical fit to the measured data and detector response. Several analytical solutions have been proposed to describe the unmodified beam profiles obtained through 3D water phantom scanning.^{4,13-15} In the work by Starkschall⁴ an ex-

ponential Cunningham model was used, while Lam¹³ utilized a Hill function combined with an asymptotic exponential, and Garcia-Vicente^{9,15} used a difference of error function. The difference of error function method¹⁶ of the form

$$G_1(x) = \frac{\sigma_1}{2} \left(\operatorname{erf}\left[\frac{X+\sigma_2}{\sigma_3}\right] - \operatorname{erf}\left[\frac{X-\sigma_2}{\sigma_3}\right] \right) \quad (4)$$

was adopted for this work, where the fitting parameters $\sigma_{1,2,3}$ pertain to the amplitude, position, and width of a Gaussian curve of the form given in Eq. (2). Additional difference of error curves, with shaping parameters $\sigma_{4,5,6}, \sigma_{7,8,9}, \dots$ summed together improve the function's ability to accurately fit the profile data as

$$H(x) = \sum_{i=1}^n G_i(x), \quad (5)$$

where $H(x)$ is the final curve resulting from the summation of n difference of error functions $G_i(x)$. Profiles were fit through an iterative process in which the first Gaussian is optimized with a difference of error function of the form of Eq. (4), as close to the profile data as achievable. A second Gaussian is then introduced, which adds an additional difference of error function to the analytical solution and the optimization is continued. The fit quality was measured using a χ^2 analysis. The number of Gaussians is easily adjusted depending on the size of the field. Five Gaussians were found to produce a good fit for the majority of cases from 2×2 to 40×40 cm² field size. It is important to start the iterative process with a good initial guess at the parameter set to ensure fast efficient optimization.

The detector response can then be deconvolved from the analytical fit to the profiles by removing the Gaussian shaping parameter σ_k from the analytical fit parameter σ_3 in each difference of error function using

$$\sigma_p^2 = \sigma_3^2 - \sigma_k^2, \quad (6)$$

where σ_k is twice the response function shaping parameter σ from our definitions in Eqs. (2) and (4). σ_3 is the width of the Gaussian function used in the profile fit of Eq. (4). The calculated σ_p replaces σ_3 in Eq. (4) to obtain the deconvolved profile. Therefore, advanced knowledge of the detector response function allows the true profile to be extracted from the measured profile.

For the purpose of obtaining accurate and consistent results, the field width of each profile was scaled to the expected field width using the accelerator defined field size. This was performed by scaling only the region encompassing 80% of the full width half maximum to maintain the penumbral shape. The remaining sections of the profile, i.e., the penumbra and tail were offset to match the new position of the 80% region. The degree to which profile widths were scaled, for the purpose of convolution parameter calculations, was less than 0.35 mm in all cases. The scaled profiles were then fit and used for the remaining work. The optimization of the difference of error function has difficulty in fitting the horn portion of the profiles produced by the flattening filter. Previous work has shown that the effects of the

FIG. 1. Edge detector cross-plane profile measurement obtained for a 90 cm SSD and a detector point of measurement of 15 cm depth. The measured raw data (circle) and data fit (solid) are shown. The data were obtained for an Elekta Synergy at a nominal energy of 6 MV. The profile fit to the measured data was obtained using a three Gaussian fitting algorithm with additional smoothed subtraction fit inside the penumbral region.

detector response in low gradient regions are negligible¹⁷ and therefore, deconvolution will not affect this region significantly. Deconvolution of this data set affected the low gradient region by less than 0.5%. Consequently, fitting was considered only for the penumbral region. An additional smoothed fit to the central portion of the profile was incorporated into the Gaussian fit to add the horn effects. A “Loess” function, which is a locally weighted scatter plot, was used to smooth the data using a least-squares quadratic polynomial fitting routine. A profile fit, which includes the Loess addition, is shown in Fig. 1. Figure 1 demonstrates the fit quality for an Edge detector profile acquired on an Elekta Synergy at 6 MV, 90 cm SSD, and 15 cm depth. Similar quality fits were achieved for CC13, CC04, CC01, and FC65 chambers at the various depths and SSDs. Detector deconvolution spread functions (kernels), were obtained for each detector relative to the Edge detector. The Edge detector, which has a surface area of 0.64 mm², produces a sharp penumbra. This was considered a good approximation to the true penumbra.^{9,12} It is known that diode detectors over respond to the low energy part of the spectrum. Consequently, obtaining the response function using large fields would include the effects of the over response. Therefore, the detector kernel

should be obtained for smaller fields and then applied to larger fields. The response function is assumed to be a Gaussian of the form of Eq. (2). The optimization was performed using the MATLAB (MathWorks, Nadik, MA) convfft function,¹⁸ which performs a convolution of two input functions. The Gaussian fitted and Loess adjusted profile of the Edge detector was convolved with a detector response function using convfft. The resulting convolved profile was then compared to the measured ionization chamber profile. The quality of the comparison was assessed in terms of the goodness of fit function χ^2 . The shaping parameter was iteratively optimized until no further reduction in the χ^2 was achieved. Shaping parameters were obtained that reproduced the measured profiles from the CC01, CC04, CC13, and FC65 chambers. Deconvolved profiles were then obtained by removing the shaping parameter of the associated kernel from each of the Gaussian curves used in the measured data fitting process according to Eqs. (5) and (6). The central portion of the measured profile was then added back into the deconvolved profile as described above. The result was compared to the Edge detector profiles.

Convolution kernel parameters were obtained for each detector at each depth and SSD and with the detector’s long axis aligned both parallel and perpendicular to the direction of travel. The resulting kernels were compared for each detector.

III. RESULTS AND DISCUSSION

Kernel response functions for each detector were obtained for six depths and four SSDs for a nominal energy of 6 MV. Additional fields and energy profiles were obtained with the CC13 ionization chamber. Shaping parameters are given in Table I for a 10×10 cm² field at 6 MV obtained on an Elekta Synergy linac. The shaping parameters are an average of those obtained for all SSD and depths for each detector. Also included are the maximum and minimum shaping parameters observed. Measured field widths for all detectors for a 10×10 cm² field were observed to vary by less than 0.6% or 0.7 mm. The effect of field width deviations, due to day to day setups, on the response function was investigated by adjusting profile widths measured with the ionization chamber by ± 1 mm. The response function was calculated using the measured Edge detector profile without any field

TABLE I. Convolution kernel shaping parameters for ionization chambers obtained relative to the Edge detector for cross-plane and in-plane measurements. Data were collected on an Elekta Synergy at nominal energy 6 MV and field size 10×10 cm². Averaged shaping parameters are from all shaping parameters obtained for all measurement depths in the range 0.8–25 cm and all SSDs in the range 90–110 cm. The maximum and minimum observed shaping parameters are also presented.

Detector	Cross-plane shaping parameter			In-plane shaping parameter		
	Average	Min.	Max.	Average	Min.	Max.
CC04	1.99	1.81	2.28	1.78	1.55	1.97
CC13	2.64	2.41	2.94	2.57	2.37	2.77
FC65-P	3.03	2.82	3.38	7.65	7.22	7.86
CC01	1.72	1.32	2.11	1.52	1.19	1.74

FIG. 2. Kernels obtained for a CC04 ionization chamber relative to the Edge detector (a) at 95 cm SSD for an Elekta Synergy and nominal energy 6 MV. The detector point of measurement varied from 0.8 to 25 cm. (b) shows a selection of calculated kernels, averaged over the measurement depth range of 0.8–25 cm, obtained for a CC13 ionization chamber, relative to the Edge detector, at 90 cm SSD. The field size and energy are given. The accelerator make to which the data are associated are listed as Elekta Synergy (E), Varian Trilogy (V), and Siemens Oncor (S).

width adjustment. It was found that a field width variation of ± 1 mm between the measured and Edge detector profile produced a variation of less than 1% in the shaping parameter of the kernel. Figure 2 shows a set of Gaussian kernels obtained for a CC04 ionization chamber relative to the Edge detector [Fig. 2(a)] obtained on an Elekta Synergy at 6 MV and 95 cm SSD. Figure 2(b) shows a selection of Gaussian kernels obtained using a CC13 ionization chamber at 90 cm SSD for several fields, energies, and linac vendors as indicated. The depth ranged from 0.8 to 25 cm for both cases. The shaping parameter σ from Eq. (2) was found to be dependent on the measurement setup. Changes in SSD and depth, for a single plane, produced up to 10% deviations in the shaping parameter for each ionization chamber. These changes translate into the variations in kernel height and width shown in Fig. 2. Kernels for the CC01 and FC65 ionization chambers, not shown, also demonstrate variations in kernel amplitude and width with setup. The determined kernel is primarily a function of the variations between the penumbral region of the ionization chamber measured and true profiles caused by the smearing effect of the volume effect. Minor variations are observed in the inner profile regions. Figure 3 shows the 70%–30% penumbral widths for each detector for profiles obtained at 90 cm SSD and 0.8 to 25 cm depths. The widths were normalized at 15 cm depth, for a visual comparison of the data, and the corresponding fits performed. The 70%–30% penumbral width was chosen as it avoids the profile shoulder and provides a relatively linear region with which to compare each detector. The penumbral width was found to increase with increasing depth. However, the degree of change varied according to the type of detector used. Therefore, the response function obtained for one detector relative to another will differ depending on the depth at which it is calculated. For the response function to remain the same for two detectors at each depth, the change in the penumbral width with depth should be the same in both cases. The variations observed in the changing penumbral width of Fig. 3 therefore contribute to the variable response function with depth observed in Fig. 2. Measured profile deconvolutions obtained from Eqs. (5) and (6) are shown in Fig. 4 for CC04

FIG. 3. The 70%–30% penumbral widths obtained for several detectors on an Elekta Synergy at nominal energy 6 MV. The data collected correspond to a 10×10 field, 90 cm SSD setup, and depth of measurement ranging from 0.8 to 25 cm. Data are normalized at 15 cm depth for visualization purposes. The solid lines show linear fits to the data.

and CC13 ionization chambers for 10×10 and 4×4 cm² fields, respectively, for the Elekta Synergy at 6 MV. CC04 data were obtained at 95 cm SSD and 10 cm depth, while CC13 data are for 90 cm SSD and 15 cm depth. The measured ionization chamber profile (circle), Edge (solid), and deconvolved (square) data are shown. The kernel used is the one obtained for the field size, depth, SSD, and energy of the measurement. The deconvolved profile matches well with the Edge detector profile in both cases. The slope of the penumbra measured between the 80% and 20% regions was calculated for the measured ionization chamber data, deconvolved data, and Edge detector data. The deconvolved CC04 example shows a 2.2% variation in the 80%–20% slope of the linear region of the penumbra compared to that of the Edge detector, while the CC13 was 2.4%. Deconvolution of a FC65 profile, which requires the largest correction and is not shown, demonstrated a deviation in the slope of the penumbra from that of the Edge detector of 2.7%. Deviation of the slope of the 70%–30% penumbral region was less than 0.5% in each case. Deconvolution of profiles from the other detectors and setups demonstrated penumbral slopes that were comparable to that of the Edge detector for the same setup when using the corresponding response function. The diameter and length of the CC13 ionization chamber are 6.0 and 5.8 mm, respectively. The FC65 chamber, has a length of 23.1 and 6.2 mm in diameter. In this case the measured penumbra differs greatly depending on the scan direction. Figure 5 shows the calculated kernels obtained for CC13 and FC65 chambers for a 6 MV beam obtained on an Elekta Synergy at 90 cm SSD and 10 cm depth. The dashed line (CC13) and circles (FC65) results are for profiles taken with the detector's long axis parallel to the direction of motion, while the solid line (CC13) and squares (FC65) results are for profiles taken with the detector's long axis perpendicular to the direction of motion. The CC13 ionization chamber, which is relatively symmetric in shape, produces an average kernel shaping parameter that varies by up to 3% with scan direc-

FIG. 4. (a) Measured CC04 (circle) cross-plane ionization chamber data obtained for an Elekta Synergy at 95 cm SSD and 10 cm depth for a 10×10 cm² field and 6 MV beam. Corresponding deconvolved CC04 (square) and Edge (line) cross-plane profiles are shown. (b) shows a measured CC13 (circle) ionization chamber cross-plane profile obtained for an Elekta Synergy at 90 cm SSD and 15 cm depth for a 4×4 cm² field and 6 MV beam. The deconvolved CC13 (square) profile and measured Edge (line) cross-plane profile are shown.

tion. The FC65 chamber, however, demonstrates considerable directional variability, which is likely due to its nonsymmetric construction. The FC65 chamber's average kernel shaping parameter was observed to vary by up to 40% between profiles obtained in-plane compared to those from cross-plane measurements. The variation between planes for CC04 and CC01 ionization chambers was 11% and 13%, respectively. This is similar to the 10% variation observed for measurements within a single plane. The ratio of width to length of 0.9 for the CC04 could also contribute to the observed variation between planes. The width to length ratio of 1.8 of the CC01 ionization chamber would suggest a greater variation between the in-plane and cross-plane profiles. However, the small dimensions of the chamber result in a measured penumbral width of less than 0.5 and 1 mm variation from the Edge detector for in-plane and cross-plane 10×10 cm² profiles obtained at 10 cm depth for a 6 MV

beam. By comparison the FC65 chamber shows a 10 and 5 mm deviation in penumbral width from the Edge detector for in-plane and cross-plane profiles. Averaged deconvolution parameters obtained, for additional field sizes and energies for the Elekta Synergy are given in Table II. The data shown are for a CC13 ionization chamber, relative to the Edge detector orientated with the stem perpendicular to the direction of travel. Table III shows averaged convolution kernel shaping parameters for a Varian Trilogy for 10×10 and 4×4 cm² fields and Siemens Oncor for 11×11 and 5×5 cm² fields. Profiles were obtained at an SSD of 90 cm and depths ranging from 0.8 to 25 cm. The obtained parameters were observed to vary with setup. However, the averaged parameter obtained for each machine, field size and energy were within 8% and were consistent with the previous results from the CC13 ionization chamber. Figure 6 shows results for the deconvolution of a CC13 ionization chamber profile measured at 90 cm SSD, 10 cm depth, 10×10 cm² field and 6 MV beam. The deconvolution was performed initially using a kernel shaping parameter averaged from all CC13 kernels at all SSDs and depths. The deconvolution was then repeated after changing the overall shaping parameter by 10%, which represents an extreme of the shaping parameter variation. Compared with the unaltered, average shaping parameter results, those obtained with

FIG. 5. Calculated convolution kernels obtained for a 6 MV beam on an Elekta Synergy at 90 cm SSD and 10 cm measurement depth. Kernels are shown for the CC13 ionization chamber relative to the Edge detector for both in-plane (dashed) and cross-plane (solid) profile measurements. Kernels are shown for the FC65 ionization chamber relative to the Edge detector for both cross-plane (square) and in-plane (circle) profile measurements

TABLE II. Convolution kernel shaping parameters obtained for a CC13 ionization chamber obtained relative to the Edge detector at an SSD of 90 cm. Averaged shaping parameters are from all shaping parameters obtained for all measurement depths in the range 0.8–25 cm. Data were collected on an Elekta Synergy at nominal energy 6 MV and field size of 10×10 cm².

Field size (cm ²)	Energy (MV)		
	6	10	18
4×4	2.64	2.66	2.48
10×10	2.56	2.53	2.58

FIG. 6. Measured CC13 ionization chamber cross-plane profile (line-circle) obtained on an Elekta Synergy for a 10×10 cm² at nominal energy 6 MV, 90 cm SSD, and 10 cm measurement depth. Deconvolution was performed using the averaged kernel parameter (dot) and the averaged kernel parameter +10% (solid) and -10% (dashed).

the $\pm 10\%$ shaping parameter show a change in the penumbral width of 0.7 mm for positive change and 0.5 mm for negative. In contrast, the results for the same scenario for a 4×4 cm² field and 10 MV beam on an Elekta Synergy demonstrated 0.8 and 0.5 mm variation for positive and negative shaping parameter variation over a 10% range from the average, while a CC04 chamber (at 90 cm SSD and 10 cm depth) showed a change in the penumbral width of 0.47 and 0.38 mm with positive and negative variation for a 10×10 cm² field.

IV. CONCLUSION

Deconvolution kernels were obtained for a variety of ionization chambers relative to a Sun Nuclear (Melbourne, FL) Edge detector. The methodology was described for processing, scaling, and fitting profiles with multiple Gaussian fit parameters applied using a difference of error function. The quality of the fit was assessed in terms of the goodness of fit function χ^2 . The equation used to obtain the Gaussian detector response function has been provided as Eq. (2). The response function was iteratively convolved with the processed Edge detector profiles until a good match of the output convolution with the ionization chambers results was obtained. Deconvolution of the ionization chamber measured profiles

was then achieved by extracting the response function shaping parameter from the multi-Gaussian fit of the data. The process was repeated for multiple SSDs and depths for a 10×10 cm² field with several commonly used ionization chambers. Data were also obtained at other available energies and field sizes and on Elekta Synergy, Varian Trilogy, and Siemens Oncor linear accelerators. The kernel shaping parameter was found to vary due to, not only the detector used but also the scan direction relative to the detector orientation, depth, SSD, energy, and field size. Consequently, the technique is limited to providing only an approximation of the profile as measured by the Edge detector. However, variations in the order of 10% in the shaping parameter, while showing deviations from the Edge detector profile, still improve significantly on the raw ionization chamber collected data, particularly in the case of large detectors. An averaged kernel was found to provide deconvolved profiles that match the penumbral width of the Edge detector to within fractions of a millimeter. Alternatively, the kernel could simply be obtained for the most frequently used setup. It would, however, be prudent to obtain the detector response at several depths to provide an estimate of the expected variations from the Edge detector profile. Consideration of the scan direction is also highly relevant, particularly for nonsymmetric detectors such as the Farmer type chamber where the shaping parameter varied by up to 40% between the in-plane and cross-plane. The smearing effect on the measured profile reduces with decreasing detector size, and therefore requires less correction. The CC01 ionization chamber has a sufficiently small radius to produce a penumbral width which approaches that of the Edge detector. The small signal to noise ratio of small detectors results in increased noise in the measured profile, when compared to larger chambers such as the CC13. This has the potential to further reduce the profile fit quality and therefore the quality of the kernel obtained. Ionization chamber noise can be overcome to some extent through point-by-point scanning where the detector remains at each scan position for an extended period. This increases the overall time scale for profile measurements. For large fields, i.e., greater than 20×20 cm² for 5 depths in-plane and cross-plane this can result in an increase from a few minutes acquisition time to in excess of 30 min. Due to the variability observed in the kernel shaping parameter, deconvolution using an averaged parameter, of small ionization chambers such as the CC01 may not improve upon the raw measurement due to the small degree of correction required.

This work provides a methodology for fitting profiles and obtaining a detector response function parameter using the Edge detector as an approximation of the unperturbed beam profile. The convolution shaping parameters are provided as a guide along with expected variations in the shaping parameter and resulting deconvolution. The Edge detector was used as an approximation to the true profile. Deconvolution of a linear accelerator commissioning data set would be possible using this technique providing the deconvolution parameter is calculated, to improve on data collected with ionization chambers of radius greater than 1 mm. However, the

TABLE III. Convolution kernel shaping parameters obtained for a CC13 ionization chamber obtained relative to the Edge detector at 90 cm SSD. Shaping parameters shown are averaged from shaping parameters obtained for all measurement depths in the range 0.8–25 cm. Data are shown for a Varian Trilogy and Siemens Oncor at a nominal energy of 6 MV.

Varian Trilogy		Siemens Oncor	
Field size	Averaged shaping parameter	Field size	Averaged shaping parameter
10×10	2.65	11×11	2.69
4×4	2.56	5×5	2.58

technique is limited to providing an approximation of the unperturbed profile due to the variations observed in the calculated kernel shaping parameters. In general, for fields where low energy response can be neglected, the Edge detector would be preferable for profile measurements.

ACKNOWLEDGMENTS

This work was supported in part by a grant from NIH, Grant No. HHSN261200522014C.

^{a)} Author to whom correspondence should be addressed. Electronic mail: cfox3@tulane.edu; Present address: Department of Radiation Oncology, Tulane University, 1415 Tulane Ave., HC65, New Orleans, Louisiana 70112.

¹ E. J. Adams and A. P. Warrington, "A comparison between cobalt and linear accelerator-based treatment plans for conformal and intensity-modulated radiotherapy," *Br. J. Radiol.* **81**, 304–310 (2008).

² J. L. Bedford, P. J. Childs, V. Nordmark Hansen, M. A. Mosleh-Shirazi, F. Verhaegen, and A. P. Warrington, "Commissioning and quality assurance of the Pinnacle3 radiotherapy treatment planning system for external beam photons," *Br. J. Radiol.* **76**, 163–176 (2003).

³ J. Venselaar, H. Welleweerd, and B. Mijnheer, "Tolerances for the accuracy of photon beam dose calculations of treatment planning systems," *Radiother. Oncol.* **60**, 191–201 (2001).

⁴ G. Starkschall, "A convolution method for constructing primary beam profiles in the presence of beam modifiers," *Med. Phys.* **15**, 657–661 (1988).

⁵ C. H. Sibata, H. C. Mota, A. S. Beddar, P. D. Higgins, and K. H. Shin, "Influence of detector size in photon beam profile measurements," *Phys. Med. Biol.* **36**, 621–631 (1991).

⁶ E. Pappas, T. G. Maris, A. Papadakis, F. Zacharopoulou, J. Damilakis, N. Papanikolaou, and N. Gourtsoyiannis, "Experimental determination of the

effect of detector size on profile measurements in narrow photon beams," *Med. Phys.* **33**, 3700–3710 (2006).

⁷ M. Buccioli, F. Banci Buonamici, S. Mazzocchi, C. De Angelis, S. Onori, and G. A. P. Cirrone, "Diamond detector versus silicon diode and ionization chamber in photon fields of different energy and field size," *Med. Phys.* **30**, 2149–2154 (2003).

⁸ C. McKerracher and D. I. Thwaites, "Assessment of new small-field detectors against standard-field detectors for practical stereotactic beam data acquisition," *Phys. Med. Biol.* **44**, 2143–2160 (1999).

⁹ F. Garcia-Vicente, J. M. Delgado, and C. Rodriguez, "Exact analytical solution of the convolution integral equation for a general profile fitting function and Gaussian detector kernel," *Phys. Med. Biol.* **45**, 645–650 (2000).

¹⁰ C. R. Edwards, S. Green, J. E. Palethorpe, and P. J. Mountford, "The response of a MOSFET, p-type semiconductor and LiF TLD to quasi-monoenergetic x-rays," *Phys. Med. Biol.* **42**, 2383–2391 (1997).

¹¹ P. D. Higgins, C. H. Sibata, L. Siskind, and J. W. Sohn, "Deconvolution of detector size effect for small field measurements," *Med. Phys.* **22**, 1663–1666 (1995).

¹² G. Yan, C. Fox, C. Liu, and J. G. Li, "The extraction of true profiles for TPS commissioning and its impact on IMRT patient-specific QA," *Med. Phys.* **35**, 3661–3670 (2008).

¹³ C. F. Lam, "A new sigmoidal function describing the small field dose profile data from a linear accelerator," *Med. Phys.* **22**, 543–547 (1995).

¹⁴ P. Metcalfe, T. Kron, A. Elliott, T. Wong, and P. Hoban, "Dosimetry of 6 MV x-ray beam penumbra," *Med. Phys.* **20**, 1439–1444 (1993).

¹⁵ F. Garcia-Vicente, J. M. Delgado, and C. Peraza, "Experimental determination of the convolution kernel for the study of the spatial response of a detector," *Med. Phys.* **25**, 202–207 (1998).

¹⁶ P. S. Cho, H. G. Kuterden, and R. J. Marks, "A spherical dose model for radiosurgery plan optimization," *Phys. Med. Biol.* **43**, 3145–3148 (1998).

¹⁷ K. S. Chang, F. F. Yin, and K. W. Nie, "The effect of detector size on the broadening of the penumbra—a computer simulated study," *Med. Phys.* **23**, 1407–1411 (1996).

¹⁸ L. Rosa, Via Centrale 27, 67042 Civita di Bagno, L'Aquila, Italy (2004).