Accuracy of treatment planning calculations for conformal radiotherapy
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Chapter VI

Detector line spread functions determined analytically by transport of Compton recoil electrons

Detector line spread functions determined analytically by transport of Compton recoil electrons

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To achieve the maximum benefit of conformal radiation therapy it is necessary to obtain accurate knowledge of radiation beam penumbras based on high-resolution relative dosimetry of beam profiles. For this purpose there is a need to perform high-resolution dosimetry with well-established routine dosimeters, such as ionization chambers or diodes. Profiles measured with these detectors must be corrected for the dosimeter’s nonideal response, caused by finite dimensions and, in the case of an ionization chamber, the alteration of electron transport and a contribution of electrons recoiled in the chamber wall and the central electrode. For this purpose the line spread function (LSF) of the detector is needed. The experimental determination of LSFs is cumbersome and restricted to the specific detector and beam energy spectrum used. Therefore, a previously reported analytical model [Med. Phys. 27, 923–934 (2000)] has been extended to determine response profiles of routine dosimeters: shielded diodes and, in particular, ionization chambers, in primary dose slit beams. The model combines Compton scattering of incident photons, the transport of recoiled electrons by Fermi–Eyges small-angle multiple scattering theory, and functions to limit electron transport. It yields the traveling direction and the energy of electrons upon incidence on the detector surface. In the case of ionization chambers, geometrical considerations are then sufficient to calculate the relative amount of ionization in chamber air, i.e., the detector response, as a function of the detector location in the slit beam. In combination with the previously reported slit beam dose profiles, the LSF can then readily be derived by reconstruction techniques. Since the spectral contributions are preserved, the LSF of a dosimeter is defined for any beam for which the effective spectrum is known. The detector response profiles calculated in this study have been verified in a telescopic slit beam geometry, and were found to correspond to experimental profiles within 0.2 and 0.3 mm (full width at half-maximum) for a Wellhoefner IC15 chamber in a 6 and 25 MV-X x-ray beam, respectively. For a shielded diode these figures were found to be 0.2 and 0.1 mm, respectively. It is shown that a shielded diode in a primary beam needs only a small size-based correction of measured profiles. The effect of the LSF of an IC15 chamber on penumbra width has been determined for a set of model penumbra. The LSFs calculated by the application of the analytical model yield a broadening by 2 mm of a 3 mm wide penumbra (20%–80%). This is 0.5 mm (6 MV-X) to 1 mm (25 MV-X) smaller than found with the experimental LSFs. With a spatial correction based on the LSFs that were determined in this study, this broadening of up to 2 mm is eliminated, so that ionization chambers like the IC15 can be used for high-resolution relative dosimetry on a routine basis. © 2001 American Association of Physicists in Medicine.

Key words: relative dosimetry, ionization chamber, detector response, line spread function, penumbra broadening

I. INTRODUCTION

Accurate knowledge of penumbrae of the applied photon beams is a prerequisite in the treatment planning of conformal radiation therapy as well as in stereotactic radiotherapy. High-resolution relative dosimetry of beam profiles is needed to obtain this knowledge during commissioning and verification of beam data in the local treatment planning system. A large amount of measurements is usually involved, in particular during verification, and there is thus a demand for routine dosimetry methods with high spatial resolution. Dosimeters used for this purpose exhibit phenomena of nonideal detector behavior, such as limited spatial resolution, nonlinearity, direct photon response, energy dependence, and, often, a combination of these factors. These phenomena are caused by finite detector size, by detector construc-
verification in dynamic wedge beams since one-dimensional reading dosimeters are presently applicable for dosimetric poses including commissioning and verification: ionization procedures, nonlinearity, direct photon response, restricted ap-
sition of the sensitive element in common, and consequently a recently been published. These detectors have a small dimen-
sion of several of these detectors in small photon beams has solid reputation of uncomplicated use in scanning devices.

In practice, two other types of dosimeters are most com-
monly used in megavoltage photon beams for routine pur-
poses including commissioning and verification: ionization chambers and shielded diodes. These two types of direct reading dosimeters are presently applicable for dosimetric verification in dynamic wedge beams since one-dimensional arrays of these detectors have become available. Ionization chambers have clear advantages as a dosimetric standard in regions with electronic equilibrium, because of the direct proportionality between output and dose, in addition to their solid reputation of uncomplicated use in scanning devices. Note, however, that this proportionality only holds for nearly

![Diagram](Image)

**Fig. 1.** A schematic illustration of photon fluence profiles \(\psi(x)\) (left column) with corresponding dose profiles \(D(x)\) (middle column) and detector output profiles \(O(x)\) (right column). The top row shows an ideal slit fluence profile, an elementary dose profile, and a corresponding detector output profile; the bottom row represents a macroscopic beam size representative for radiotherapy practice. The line spread function \(S(x)\) relates \(D(x)\) to \(O(x)\) by convolution; Eq. (3). Note that the \(x\) scale of the lower row of graphs is compressed with respect to the upper row.


tion, and by characteristics of the applied detector materials. The density and effective atomic number of the sensitive element are usually different from the surrounding medium of interest, and thus photon interaction and electron transport are altered. Measured profiles can be corrected for these detector phenomena when the detector’s line spread function (LSF) is known.

This LSF can be defined as the transfer function that transforms the “real” dose profile, \(D(x)\), into the measured detector response profile, \(O(x)\), as schematically illustrated in Fig. 1. Note that the LSF, as defined here, is not equal to the response to a mathematical line or delta function, because elementary dose profiles differ from delta functions in megavoltage photon beams due to electron transport effects. The LSF, however, describes the broadening of elementary dose profiles that result from slit x-ray beams.

Several types of detectors are available for high-resolution dosimetry, for instance, natural diamond detectors, liquid ionization chambers, plastic scintillators, and radio-
graphic and radiochromic film. A comparative study\(^1\) on the use of several of these detectors in small photon beams has recently been published. These detectors have a small dimen-
sion of the sensitive element in common, and consequently a limited correction for their size is needed. However, all suff-
er from either spectral dependence, extensive operation pro-
cedures, nonlinearity, direct photon response, restricted ap-
plicability, or a combination of these limitations.

In practice, two other types of dosimeters are most com-
mmonly used in megavoltage photon beams for routine pur-
poses including commissioning and verification: ionization chambers and shielded diodes. These two types of direct reading dosimeters are presently applicable for dosimetric verification in dynamic wedge beams\(^2\) since one-dimensional arrays of these detectors have become available. Ionization chambers have clear advantages as a dosimetric standard in regions with electronic equilibrium, because of the direct proportionality between output and dose, in addition to their solid reputation of uncomplicated use in scanning devices. Note, however, that this proportionality only holds for nearly water-like chambers.\(^3\) Diodes are often used in the build-up region\(^4\) because of the small dimension (in the scan direction) of the sensitive element. Moreover, ionization cham-
bers and shielded diodes are frequently used as “all-round” dosimeters, including use in the penumbra region, albeit usu-
ally without correction for the (unknown) LSF. The magni-
tude of this (omitted) correction can be assessed from studies\(^5-7\) that indicate that ionization chambers with 4–6 mm internal diameter typically show a broadening of the 20%–80% penumbra width of 2–3 mm. Especially in the penumbra region a considerable gain in accuracy in the dosimetry can thus be achieved when the LSF of these dosim-
eters is known and corrected for. However, experimental de-
termination of the LSF is cumbersome\(^8\) and restricted to the specific detector type and beam spectrum applied.

The LSF of an ionization chamber can be expected to be governed by the detector size, change in electron fluence caused by the replacement of water by air in its interior, and the generation of an increased number of electrons in the detector wall and central electrode, which often have a density higher than unity (water). The LSF of a diode is expected to be determined mainly by its size, but the diode response may show an energy dependence,\(^9\) especially if not properly shielded.

In a previous study,\(^10\) a model has been developed and applied to calculate dose profiles in a telescopic slit beam geometry. The analytical model combines Compton scattering of incident photons, transport of resulting electrons by Fermi–Eyges small-angle multiple scattering theory, and functions to limit electron transport. In this slit beam geom-
etry all dose contributions except the primary dose could be excluded. It has been verified that the model is suitable to calculate slit beam dose profiles in situations that are dominated by monodirectional primary photon fluence. Discrete photon spectral contributions are preserved, which allows an application of the results to other linear accelerator (linac) beam x-ray spectra. As will be shown in this study, the model can be extended to yield slit-beam detector response profiles, in particular, ionization profiles in the case of an ionization chamber. From the combination of slit dose pro-
files and slit response profiles, the LSF of a specific dosim-
eter can then readily be derived.

Our aim in the present study is to extend the application of the model to the determination of slit response profiles of two common dosimeters, shielded diodes, and thimble ion-
ization chambers, and to verify these slit response profiles in experiments with telescopic slit geometry. The emphasis in this study lies on ionization chambers. The modeled slit re-
sponse profiles of ionization chambers include electron transport in air, and an increased recoil of Compton electrons in the chamber wall and the central electrode. Our further ob-
jective in this study is to define parametrizations of LSFs that are suited for use in deconvolution or reconstruction tech-
niques and to quantify the effect of calculated and experi-
mental LSFs on penumbra width, thus enabling a more ac-
curate penumbra determination.
In the first part of this section the theoretical framework of the previous study\textsuperscript{10} is extended to allow a calculation of the response profile of an air-filled cylindrical ionization chamber, whereas in the second part the theoretical LSF is determined and a parameterization defined that accounts for the dimensions and construction of the chamber.

A. Slit beam response profile of a thimble ionization chamber

The reported theoretical formalism\textsuperscript{10} allows the analytical calculation of electron fluence in a water phantom irradiated by a narrow primary x-ray slit beam. The analytical model combines Compton scattering of incident photons, using Klein–Nishina cross sections,\textsuperscript{11,12} transport of resulting electrons, derived from the ICRU35 Report\textsuperscript{15} under the continuous-slowing-down-approximation, dose profiles were calculated. The coordinate system used has previously been described\textsuperscript{10} and is merely summarized here in Fig. 2. As a notation convention primes are used in this study in relation to Compton photon interaction, quantities without primes relate to traveling electrons, whereas coordinates with double primes represent the position of the detector center.

One effect that has to be taken into account when extending the previous formalism to ionization chamber measurements is the modification in the generation of Compton scattering caused by the presence of the chamber, in particular, the replacement of phantom material (water) by air and by materials applied in chamber wall and central electrode that differ in density and atomic number from water. Since Compton scattering is proportional to electron density, the wall and electrode materials affect the amount of recoil electrons when exposed to the primary photon fluence in the slit beam. On the other hand, the air in the chamber interior will produce very little Compton scattering. Any Compton scattering in chamber air is therefore neglected. A cylindrical symmetry is assumed for the chamber geometry, as illustrated in Fig. 3. The effect of detector construction on Compton scatter can now mathematically be represented by a relative Compton scattering intensity function $I_{\text{det}}$, which is defined as the electron density of detector material relative to water, i.e., $\rho_{\text{material}} \cdot (Z/A)_{\text{material}}$, with $\rho$ the mass density and $Z/A$ the ratio of atomic to mass number. Let $R_{\text{in}}$ be the internal radius of the ionization chamber, let $W$ be the thickness of the wall, let $L_{\text{in}}$ be the length of the chamber, whereas $R_{\text{wall}}$ and $L_{\text{wall}}$ represent the radius and length of the central electrode, respectively. Furthermore $r'=(x',y',z')$ and $r''=(x'',y'',z'')$ indicate the location of Compton interaction and the location of the center of the ionization chamber in Cartesian coordinates, respectively. The following conditions represent the relative intensity, $I_{\text{det}}(r',r'')$ of Compton interaction in water, wall cylinder, wall caps, central electrode, and chamber air, respectively:

\[
I_{\text{det}}(r',r'') = \begin{cases} 
1, & \text{if } |r' - r''| > R_{\text{in}} + W \\
0, & \text{or } |r' - r''| \leq \frac{L_{\text{in}}}{2} + W.
\end{cases}
\]
with energy $E'$ and a traveled range $\zeta$ through water. Increased electron energy loss in wall material ($\rho_{\text{wall}} > 1$) is thus neglected. The detector response (output) at position $r''$, $O(r'')$, can now, in analogy to Eqs. (1)–(3) of the previous study, be expressed as

$$O(r'') = \int_{A_{\text{det}}} \frac{dN}{d\Omega} P(r,\Omega; r', \Omega', E') I_{\text{det}}(r', r'') \frac{S_{c}^{\text{air}}(E(\zeta, E'))}{\rho} \times H(\zeta) R(\zeta) d\zeta d\Omega'. \quad (2)$$

The integration limits in this equation indicate the primary x-ray spectrum in the slit beam, the detector inner wall surface ($A_{\text{det}}$), the spherical range of electron travel directions, the dimensions of the slit beam in the phantom ($d, l, w$), and the hemisphere of (forward only) Compton recoil directions.

In the numerical implementation of this transport model calculation efficiency is considerably improved by calculation of the following integral in points $L$, Fig. 2, with $|r'| = 0$ and thus $\zeta = r/R_p$:

$$\int_{\pi} \int_{0}^{2\pi} \frac{dN}{d\Omega} P(r,\Omega; 0, \Omega', E') \frac{S_{c}^{\text{air}}(E(\zeta, E'))}{\rho} \times H(\zeta) R(\zeta) d\zeta d\Omega. \quad (2a)$$

Second, electrons recoiled in the central electrode in a thimble ionization chamber have to be modeled. These constitute a small contribution in total detector response in comparison to the contribution of electrons recoiled from the surrounding phantom and the detector wall, as will be shown in this study. Because of this small contribution some approximations could be introduced in the modeling of electrons coming from the central electrode to simplify and speed up calculations. In this study it is assumed that for all Compton interactions in the electrode the electrons recoil from the center of the electrode, and that in the calculation of $T_{\text{det}}$ for these electrons the diffusion of electron trajectories between the center and the surface of the central electrode can be neglected ($\Omega = \Omega'$). Under these assumptions the trajectory length $T_{\text{det}}$ for electrons recoiled in the central electrode can be incorporated in the precalculated integral, Eq. (2a), which can be evaluated a priori using the values for the mass collision stopping power at distance $r = R_{\text{det}} \rho_{\text{water}}$, i.e., by scaling the electrode radius by its density.

B. Line spread functions

The slit dose and slit response profiles of the previous and present study, respectively, can now be combined to define a LSF of any dosimeter for which the slit response profile is known. For a specific beam energy spectrum and slit geom-

\begin{align}
I_{\text{det}}(r', r'') &= \rho_{\text{water}} \left( \frac{Z_{\text{wall}}}{A_{\text{water}}} \right), \quad \text{if } R_{\text{in}} < |r' - r''| < R_{\text{in}} + W \\
\text{and } |r'_x - r''_x| &< \frac{L_{\text{in}}}{2}, \\
I_{\text{det}}(r', r'') &= \rho_{\text{water}} \left( \frac{Z_{\text{water}}}{A_{\text{water}}} \right), \quad \text{if } |r' - r''| < R_{\text{in}} + W \\
\text{and } \frac{L_{\text{in}}}{2} - |r'_x - r''_x| &< \frac{L_{\text{in}}}{2} + W, \quad (1) \\
I_{\text{det}}(r', r'') &= \rho_{\text{ed}} \left( \frac{Z_{\text{ed}}}{A_{\text{ed}}} \right), \quad \text{if } |r' - r''| < R_{\text{ed}} \\
\text{and } |r'_x - r''_x| &< \frac{L_{\text{ed}}}{2}, \\
I_{\text{det}}(r' - r'') &= 0, \quad \text{elsewhere.}
\end{align}

Another effect that has to be accounted for is the observation that an ionization chamber does not directly measure dose, but has an output that is defined by the amount of ionization that occurs in its sensitive element, the chamber air. In this study this amount is assumed to be proportional to the total track lengths of all electrons that enter the chamber air, coming from either the phantom material, the wall, or the central electrode, multiplied by the mass collision stopping power associated with the electron energy upon entrance.

First, the track lengths of electrons coming from the phantom and the wall material are to be modeled. These can be treated identical, except for the difference in $I_{\text{det}}$. An effective trajectory length $T_{\text{det}}$ inside chamber air is defined, neglecting the presence of the central electrode for this purpose and assuming straight electron trajectories in the few millimeters of chamber air. Then straightforward geometrical considerations suffice to define $T_{\text{det}}(r, \Omega) dr_d d\Omega$ as the air volume traversed by electrons that arrive in the areal element $dr_d$ around $r$ on the chamber inner wall, while traveling in a direction in between $\Omega$ and $\Omega + d\Omega$.

The equations (1)–(3) of the previous study can now be extended to incorporate the response of cylindrical ionization chambers. For this purpose it is assumed that the fluence of electrons that travel toward the chamber air is not influenced by the replacement of water by chamber air. The effect of this assumption is limited to electrons that reenter chamber air. Restating briefly the quantities used, let $dN_{E'}/d\Omega$ be the number of Compton electrons recoiled per solid angle $\Omega'$; let $P(r,\Omega; r', \Omega', E') dx dy d\Omega$ be the probability that an electron with initial Compton recoil energy $E'$ is found in an area in between $x$ and $x + dx$, and in between $y$ and $y + dy$ and traveling in direction $\Omega'$, when arriving at depth $z$, relative to an initial Compton recoil position $r'$ and recoil direction $\Omega'$; let $\zeta = |r' - r'|/R_p$, with $R_p$ the electron practical range, represent the fractional traveled distance by the electron; let $R(\zeta)$ represent a range-straggling correction and $H(\zeta)$ be a range cutoff function; and, finally, let $S_{c}^{\text{air}}(E(\zeta, E'))/\rho$ be the mass collision stopping power in detector air of electrons with remaining energy $E$ after a recoil.
et the slit dose profile, $D(x)$, and slit response (detector output) profile, $O(x)$, are defined, Fig. 1. The LSF $S(x)$ is, then, defined by a convolution:

$$O(x) = D(x) \ast S(x).$$  \hspace{1cm} (3)

Furthermore, when the LSF, $S(x)$, for a specific detector is known, deconvolution or reconstruction techniques can subsequently be applied to this equation to recover a dose profile in any x-ray field in which a response profile is measured. This assumes that the LSF that has been determined for a primary beam spectrum is also valid in the local beam spectrum. This assumption is discussed in Sec. VA.

For numerical applications, a fitting function of the LSF is defined with a limited set of parameters that are related to relevant detector characteristics. In the case of a thimble ionization chamber, these parameters define elliptic functions, for the cross sectional areas of an effective detector radius, $R_{\text{eff}}$, the inner radius, $R_{\text{in}}$, and outer radius, $R_{\text{out}}$, of the chamber wall, and the radius, $R_{\text{ced}}$, of the central electrode. Furthermore a Gaussian kernel, with half-width $\sigma$, is added, because some studies indicate that this would give a better description of spatial response. The fitting function $S_{\text{fit}}(x)$ of the LSF of a thimble ionization chamber thus becomes

$$S_{\text{fit}}^\text{IC}(x) = A_1 \sqrt{R_{\text{eff}}^2 - x^2} + A_2 \left( \sqrt{R_{\text{out}}^2 - x^2} - \sqrt{R_{\text{in}}^2 - x^2} \right) + A_3 \sqrt{R_{\text{ced}}^2 - x^2} + A_4 e^{-x^2/2\sigma^2}. \hspace{1cm} (4)$$

In this and the next equation, terms of the form $\sqrt{(R^2 - x^2)}$ are to be replaced by zero if $|x|>R$. In the case of a shielded diode, the most important parameter is the radius of the sensitive element, $R_{\text{det}}$, yielding

$$S_{\text{fit}}^\text{DI}(x) = A_1 \sqrt{R_{\text{det}}^2 - x^2}. \hspace{1cm} (5)$$

Note that the square root terms in Eqs. (4) and (5) describe sections of ellipses, like $S/|A|^2 + x^2 = R^2$ or in generalized form $\alpha x^2 + \beta y^2 = 1$, and thus should be called elliptic, rather than parabolic.

### III. METHODS

#### A. Calculation methods

Two types of thimble ionization chambers are modeled: a common size chamber (IC15, Wellhoefzer, Germany, 130 mm$^3$) and a small chamber (NAC, National Accelerator Institute, South Africa, 7 mm$^3$). The properties of these detectors are summarized in Table I. For the purpose of modeling, the thimble detectors are approximated by cylinders with a flat top and bottom surface, Fig. 3. Compton scatter and electron transport are calculated as described previously, schematically indicated in Fig. 2, and the results of the calculation of Eq. (2a) are stored in a matrix of points $L$ in the XZ plane. Available memory allowed a grid size for the dose deposition points $L$ of 0.2 mm, with a corresponding shift in the K points of 0.1 mm in the X and Z direction to avoid singularities in the dose deposition points. A contribution to the detector response (electron fluence times track length times stopping power in air) according to Eq. (2) is sampled in points on the dosimeter wall inner surface distributed along the midcircular transection of the detector and along the cap surface. Along the upper half of the midcircular transection, 100 points are used, along the lower half 50 points. Furthermore, the contribution to the detector response was determined in 51 points evenly distributed over the flat top surface of the dosimeter. Because of the symmetry in the calculation geometry and the extended length of the slit, this set of points can represent the entire wall–air interface of the outer detector electrode. The relative weighting of the detector points is proportional to the fractional wall area that each point represents.

The contribution of electrons recoiled in the central electrode is calculated with the approximations described at the end of Sec. II A and is added to the contribution of electrons recoiled in the phantom and detector wall. Detector response profiles of the ionization chambers are calculated separately for all photon energy bins that constitute the effective energy spectra of our linac beams, Fig. 3 in the previous study. Afterward these monoenergetic profiles are integrated over the photon spectra. Due to the trade-off

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**Table I. Characteristics of thimble ionization chambers used in this study.**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Manufacturer</th>
<th>Wall</th>
<th>Inner wall</th>
<th>Outer wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC15</td>
<td>Wellhoefzer, Germany</td>
<td>Material: Shonka C552</td>
<td>Density (g/cm$^3$): 1.7</td>
<td>Outer radius (mm): 3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density (g/cm$^3$): 1.7</td>
<td>Outer radius (mm): 3.4</td>
<td>Inner radius (mm): 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Central electrode: Shonka C552</td>
<td>Density (g/cm$^3$): 1.7</td>
<td>Length (mm): 3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Central electrode: Shonka C552</td>
<td>Density (g/cm$^3$): 1.7</td>
<td>Length (mm): 3.3</td>
</tr>
</tbody>
</table>

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between the resolution and size of the matrix of L points within available memory, the calculated response profiles (this study) and dose profiles (previous study) have limited lengths of 2 and 1 cm, respectively, and consequently low, but non-negligible, start and stop values, typically 1% (6 MV-X) to 3% (25 MV-X) of the profile maximum. To minimize artefacts in the determination of LSFs, the tails of the dose profiles and the detector response profiles have been extended using a fit to the sum of two Gaussians. The validity of this procedure is assessed in Sec. V A.

The calculation took from 28 h for the lowest-energy bin to 36 h for the highest-energy bin on a 333 MHz Pentium PC.

Detector response profiles of a silicon diode are calculated by convolution of the previously\(^\text{10}\) calculated slit beam dose profiles with the circular shape of the diode’s sensitive element (radius 1.25 mm).

**B. Experiments**

A telescopic slit beam geometry that excludes all dose contributions except the primary photon dose, has previously been reported in detail,\(^\text{10}\) and is described briefly here. Photon beams of 6 MV-X and 25 MV-X with a 9 mm diam isocentric field size were used, generated by a Philips SL25 linear accelerator. Slit widths of 0.20 and 0.40 mm thickness were defined by calibrated spacers. Aiming at optimal spatial resolution, scans were made with a dedicated water phantom. In this *high-resolution setup*, scans crossing the slit width were made with 1 s integration time per step (0.05 mm) at a depth of 50 mm at 3.00 m source to phantom distance. Scans with the slit closed were made to define the transmission of the tungsten slit blocks. Per slit width, beam energy and detector type two slit-open and two slit-closed scans were averaged. By mounting a yoke to the scanning arm of the water phantom, a diamond,\(^\text{10}\) an IC15, and a diode were applied successively in the same scans, i.e., without any change in geometry.

The diode is a *p*-type Scanditronix photon diode with a high-density tungsten-epoxy shielding directly behind the sensitive element to decrease the low-energy response due to backscatter.\(^\text{21}\) The diode was oriented pointing toward the linac source. The radius of the sensitive element was specified as 1.25 mm. The ionization chambers were oriented with the symmetry axis parallel to the slit direction, the *Y* axis in Fig. 2. Linac fluctuations were recorded with a 600 cm\(^2\) reference ionization chamber placed near the water phantom, because no place for a reference detector inside the small beam was available. Reference and scanning ionization chambers were operated at 300 V generated by a Wellhoefer WP5006 electrometer, the diode was operated without bias voltage via another WP5006 electrometer. All electrometer channels were read out via a four-channel voltage-to-frequency converter (Hytec, UK) by a PC counter card (PC-TIO-10, National Instruments, TX). During slit scanning with the IC15, the diamond detector signal, although low in magnitude, was thus simultaneously available for some reference purposes.

Compared to the diamond detector scans in the previous study, the ratio of the peak (slit open) to background (slit closed) signal in ionization chamber scans is much lower, typically a ratio of 1.2:1. Therefore, specific measures were taken in acquisition and processing: sandwich of slit-open and slit-closed scans, the exclusion of transients based on a first-derivative criterion, the detection and verification of small drifts in linac output by a comparison of integrated output of the reference chamber and diamond (second reference), and correction for verified small drifts in linac output in between repeated scans.

A standard water phantom (Wellhoefer WP700) was used in separate sessions in which many repeated scans (12–64 scans depending on the peak-to-background ratio) were made with scan speeds of 0.9–1.8 mm/s and distances between measuring points of 0.3–0.5 mm, indicated here as *standard resolution* scans. The source to phantom distance for these scans was 4.00 m. Per scan, this standard resolution procedure is much faster and thus less sensitive to linac output variations than the high-resolution setup, but at the expense of less resolution and more noise. In the same setup detector response profiles of the small NAC chamber were measured.

**C. Line spread functions and penumbra broadening**

For each combination of ionization chamber and beam energy, the line spread function has been determined using the calculated or measured response profile and the corresponding calculated slit beam dose profile. Only calculated slit beam dose profiles were used because of the absence of experimental noise. This is justified by the fact that these profiles show close agreement to experimental profiles.\(^\text{10}\) The LSFs \(S(x)\) in Eq. (3) have been calculated. Theoretically this equation can be solved for the unknown function \(S(x)\) by application of the convolution theorem in the Fourier domain. However, the limited knowledge of the other two functions in the equation, which are defined at discrete points over a finite length and in case of experiments supplied with noise, often yields impracticable outcomes with much high-frequency noise.\(^\text{18}\) Therefore the maximum likelihood iterative reconstruction method\(^\text{22}\) was used, which is especially suited for cases with limited knowledge of the input function. Iteration was terminated when the sum of squared differences between the left-hand and right-hand side of Eq. (3) changed less than 1% in between two iterations. However, the maximum likelihood method has reported artefacts.\(^\text{23}\) To decrease the impact of these artefacts in our case, a least-square fit procedure was imposed on the reconstructed LSFs, using Eq. (4) and thus bounding the result to physical characteristics of the detector. The accuracy of the eventual LSFs is assessed in relation to the intended use, the (de)convolution of penumbras.

For the purpose of this assessment, the steepest possible penumbras in a macroscopic field have been created by adding slit beam dose profiles geometrically side to side to form 50x 30 mm\(^2\) primary beam profiles. ‘‘Real’’ detector beam response profiles, i.e., without the effects of reconstruction
and of fit of LSFs, were constructed by a similar geometrical addition of detector slit beam response profiles. Alternatively, detector slit beam response profiles that include effects of maximum likelihood reconstruction and the imposed fit procedure of LSFs were constructed by convolution of the slit beam dose profiles with these LSFs, followed by geometric addition. The difference between the penumbra of both beam profiles is an indication of the effect of the reconstruction and fit procedure on the outcome of (de)convolution procedures.

The most important clinical implication of the LSFs, namely their effect on penumbra, was assessed by studying the broadening of a set of model penumbra, defined as $1/2 \text{erf}(\alpha)$, where erf represents the error function, and in which $\alpha$ was varied to yield the penumbral widths (20%–80%) in between 1.5 and 11 mm.

IV. RESULTS

A. Slit beam response profiles

Detector response profiles of an IC15 chamber in a 6 MV-X and a 25 MV-X slit beam are shown in Figs. 4(a) and Fig. 4(b), respectively. The profiles run in the X direction of Fig. 2. The calculated profiles were obtained by application of the analytical electron transport model, Eq. (2), in a 0.2 mm slit beam, indicated at the bottom of Fig. 4. Experimental slit response profiles obtained in a 0.2 mm as well as in a 0.4 mm slit beam are also shown. All profiles were normalized to 100% peak level. Experimental data points have been pooled per 0.2 mm interval, except for the standard resolution scans, which have been pooled per 0.5 mm. The points and error bars represent the mean and standard error of the mean of the underlying signals. Full width at half-maximum values of the detector response profiles, measured in the 0.4 mm slit beam, are indicated in Table II. Except for the region from 4 to 7 mm distance from the center, which will be discussed in Sec. V B, the calculated 6 MV-X model profile agrees well with the measurements, and the 6 MV-X experimental 0.2 and 0.4 mm slit profiles are also mutually in good agreement. The slit response profiles of both experimental setups, high resolution, and standard resolution, are in reasonable agreement with each other for both 6 MV-X and 25 MV-X. Experimental setup errors can thus be excluded. The calculated 25 MV-X model profile is mostly lower and less wide than the experimental profiles. The 25 MV-X slit beam scans in the high-resolution setup were not completed because poor linac cooling has limited 25 MV-X beam-on time.

In Fig. 5, calculated and experimental response profiles of a NAC chamber in a 6 MV-X 0.2 mm slit beam are shown. The noise level and the peak to background level in these experiments were so poor, that repetition of the scans in the high-resolution setup was not attempted, as this would impose too high demands on linac stability.

Model and experimental diode slit response profiles in 6 MV-X and 25 MV-X 0.4 mm slit beams are shown in Fig. 6. The model slit response profiles were obtained by convolution of the slit beam dose profiles\(^{10}\) with the transaction of the sensitive area of the diode, Eq. (5).

B. Line spread functions

Line spread functions of the IC15 detector obtained with the maximum likelihood iterative restoration technique are shown in Figs. 7(a) and 7(b), for 6 MV-X and 25 MV-X beams, respectively. Calculated LSFs were based on 0.2 mm

<table>
<thead>
<tr>
<th>Detector</th>
<th>Beam nominal energy (MV-X)</th>
<th>Calculated FWHM (mm)</th>
<th>Measured FWHM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC15</td>
<td>6</td>
<td>6.8</td>
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</tr>
<tr>
<td>IC15</td>
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<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Shielded diode</td>
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<td>2.4</td>
<td>2.6</td>
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<tr>
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<td>2.6</td>
<td>2.7</td>
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</tbody>
</table>
slit beam data, whereas the presented measured LSFs were derived from the less noisy 0.4 mm slit beam data. The parameter values that result from a fit of Eq. (4) to the LSFs are listed in Table III. No wall effect was noticed in the experimental 25 MV-X response profile. For this case a simplified fitting function, Eq. (4) without wall effects, was used. The table also presents the LSF parameters for the NAC chamber in a 6 MV-X beam based on calculated response functions. The corresponding measured response function, Fig. 5, was not suited to yield a meaningful LSF, due to the large uncertainty.

![Figure 5](image5.png)

**Fig. 5.** Calculated (solid lines) and measured (points) slit detector response profiles along the $x$ axis (Fig. 2) of a NAC ionization chamber in a 6 MV x-ray beam. The internal diameter of the NAC chamber of 1.9 mm and the slit width of 0.2 mm are indicated by horizontal lines. The zero response level is represented by a full horizontal line. The error bars represent one standard deviation in the underlying signals.

![Figure 6](image6.png)

**Fig. 6.** Calculated (solid lines) and measured (points) slit detector response profiles along the $x$ axis (Fig. 2) of a shielded photon diode in a 6 (a) and 25 MV (b) x-ray beam. All profiles have been normalized to 100% maximum value. At the bottom, the slit width of 0.4 mm is indicated by a horizontal line. The zero response level is represented by a full horizontal line.

![Figure 7](image7.png)

**Fig. 7.** Calculated (solid lines) and measured (dashed lines) line spread functions (LSFs) of an IC15 ionization chamber based on 0.2 and 0.4 mm slit beams, respectively, in a 6 MV (a) and 25 MV (b) x-ray beam. The points represent the calculated LSF after the application of Eq. (3) using a maximum likelihood iterative reconstruction (MLIR) algorithm; the lines represent the LSFs after a fit according to Eq. (4). The calculated and fitted LSFs have been normalized to a central value of 1.0; the other LSFs were normalized to the same area under the curves.

<table>
<thead>
<tr>
<th>IC</th>
<th>E(MV-X)</th>
<th>Calc/Meas</th>
<th>A₁ (mm⁻¹)</th>
<th>Rₑₑ (mm)</th>
<th>A₂ (mm⁻¹)</th>
<th>Rₑₜ (mm)</th>
<th>A₃ (mm⁻¹)</th>
<th>Rₑₑ (mm)</th>
<th>A₄</th>
<th>σ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.77</td>
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<tr>
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<tr>
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<td>Calc</td>
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<tr>
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<tr>
<td></td>
<td></td>
<td>Meas</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table III.** Fit parametrization of calculated and measured (where available) line spread function, following Eq. (4), for two types of thimble ionization chambers (IC15 and NAC) and two effective energy spectra, indicated by the beam nominal energy $E$. The parameters $Rₑₑ$, $Rₑₜ$, and $Rₑₑ$ are defined by detector dimensions.
tainty in the measurements. The effect of reconstruction and subsequent fit of LSFs is discussed in Sec. V C.

The penumbra broadening caused by the measured and calculated LSFs, expressed as an increase in 20%–80% width of model penumbra, is shown in Figs. 8(a) and 8(b), for 6 MV-X and 25 MV-X, respectively. The solid lines indicate the broadening of model penumbra when the model-based LSF is used; the dashed lines indicate the broadening when various measured LSFs are applied. The marked points and the dash–dotted line are discussed in Sec. V C.

V. DISCUSSION

Aspects treated in this section are the model and its implementation (Sec. V A), the experimental verification (Sec. V B), the reconstruction of the line spread functions and the penumbra broadening caused by ionization chambers (Sec. V C), and general aspects such as the applicability of the derived line spread functions in macroscopic fields that are representative for conformal radiation therapy practice (Sec. V D).

A. Calculational model

In the previous study\(^1\) the assumptions have been discussed that were made in the modeling of electron transport: small-angle multiple scattering, linear energy loss, and transport restricted to the electron practical range. It was shown there that these approximations can have distinct localized discrepancies in special situations with, for instance, monoenergetic, monodirectional, or localized electron sources, but present good accuracy in the local dose in an x-ray slit beam geometry. This was attributed to the distribution of Compton electron sources over slit beam volume, initial traveling directions, and initial electron energies, which levels off any local inaccuracy. In the present study with macroscopic detectors, local inaccuracies are further reduced because electron fluence is integrated over the detector extension. On the other hand, only a small strip of the detector is actually in the high dose region near the slit beam, whereas inaccuracies that extend over a range comparable to the detector dimension will be accumulated over the entire detector surface. These inaccuracies will thus be more dominant in the output of a macroscopic detector. An example of such a discrepancy over an extended range is the effect of the electron range cutoff approximation in the model. The error leveling and error accumulation effects may partly compensate each other, thus the net effect on the calculation accuracy will be assessed in comparison with experiments in the next section.

The calculated model response profiles reveal some noteworthy characteristics of the response of a thimble ionization chamber in water, that are reflected in similar characteristics found in the experimental profiles and in the corresponding LSFs. The calculated 6 MV-X IC15 profile is taken here as representative for conformal radiation therapy practice (Sec. V D).
higher than chamber air (central electrode) or the surrounding medium (chamber wall). In the slit beam response profiles, the contribution of the central electrode is approximately 12% and 9% of the maximum response at 6 MV-X and 25 MV-X, respectively, which was calculated to correspond to a 1.9% and 1.1% contribution to the maximum response, respectively, in beams larger than 30×30 mm². This photon response is thus much lower than the photon response that was reported for a diamond detector.24

As was described in Sec. II, the limited calculated profile lengths were extended by a sum of two Gaussian functions to minimize artifacts in the calculation of LSFs. The influence of the choice for a particular extension type has been assessed by a comparison to LSFs that were extended by a much shorter extension, a linear tail fit until zero value is reached. In a 50×30 mm² primary beam, this yielded a difference in 20%–80% penumbra broadening of less than 0.05 and 0.2 mm, for a 6 MV-X and 25 MV-X beam, respectively. For practical purposes the particular choice of applied extension thus has a negligible influence.

An assumption that is implicit in the intended use of LSFs in macroscopic fields is the appropriateness of the effective primary photon beam spectrum at off-axis positions, while the effective spectrum has been determined on the basis of central-axis depth dose curves. By a comparison of Figs. 8(a) and 8(b) it can be seen that the different LSFs found for primary beams with 6 MV-X and 25 MV-X energy spectra lead to broadening of model penumbra that differ less than 0.25 mm. Noticing this small difference for two distinctly different energy spectra, it is concluded that the inaccuracy caused by application of the LSFs for an off-axis penumbra correction can be neglected.

B. Experiments

The experimental 0.2 and 0.4 mm slit response profiles, Fig. 4, are mutually in good agreement, in particular, concerning the width at half-height. This is to be expected considering the negligible slit size in comparison to the detector dimension.

Peak (slit-open) to background (slit-closed) ratios in the experiments ranged from 1.08:1 to 1.25:1 depending on slit width, chamber type, and energy. Two causes for these low ratios, the large source-to-phantom distance and the small slit widths, are essential requirements for good spatial resolution and negligible geometric beam edge blurring.10 The third factor is the macroscopic detector dimension with respect to the slit width. This causes the entire detector to be irradiated by the “background” beam, i.e., the beam transmitted through the tertiary collimators, whereas at any time effectively only a thin slice of the detector can be found in or near the slit beam. Considering the reported peak to background ratio and the width of the slit beam dose profiles, the above-mentioned low peak to background ratios were estimated and had to be accepted as inherent to the required experimental setup. Therefore the measures described in Sec. III B were applied. As the first measure, sandwiching, is obvious, and the second measure, transient exclusion, is confined to local effects, especially the effects of the last measure, a correction for linac drift, needs to be assessed. The applied corrections of the closed-slit background by a factor of up to 1.01 imply up to a 4% and 6% decrease in the tails of the 6 MV-X and 25 MV-X detector response profiles, respectively. At the peaks no changes occur due to the normalization to 100%. The effect of a closed-slit (background) correction factor of 1.01 in a 6 MV-X beam was calculated to correspond to 0.6 mm less 20%–80% penumbra broadening at original model penumbra widths up to 7 mm. Hypothesizing a worst case in which the applied correction is just better than no correction at all, an associated maximum inaccuracy in penumbra broadening of half of this value, i.e., 0.3 mm, is estimated.

In the present study, the influence of the phantom scatter induced by the slit beam was reported to be negligible. In the present study this cannot a priori be assumed due to the macroscopic detector size and the low peak-to-background ratios. Approximating the 0.2 mm×27 mm slit beam by an effective radius of 1.3 mm, and reading Fig. 4 of Björngard et al.,26 a phantom scatter dose contribution of 1.0% in a 6 MV-X beam is found on the beam axis. By application of data from the previous study10 in the slit geometry, it has been estimated that in the 0.2 mm slit beam approximately 0.5% of the total peak output of the measured IC15 profile was caused by slit beam induced phantom scatter. At the location of the reference detector, upstream and with an absorber thickness in between the slit beam and reference detector of approximately 20 g/cm², this scatter is virtually absent. Because it is thus not included in the background correction factor, it presents a small additional uncertainty to the response functions.

Both effects together, the background correction with its inherent uncertainty and the phantom scatter for which no correction is applied, may account for an estimated uncertainty in the tails of the measured response profiles of ±3%, which is not included in the indicated standard error in the measurements. This corresponds to an uncertainty in the model penumbra broadening of approximately ±0.5 mm.

Some asymmetries with respect to the central axis of up to approximately ±3% can be seen in the experimental high-resolution response profiles of Fig. 4(a). By an analysis of the reference signal, these could partly be traced to increases in linac output presenting asymmetries of less than 0.5% in some measurements, which show up with enhanced magnitude in the response profiles due to the low peak-to-background ratios. A point-to-point correction based on the reference signal could have remedied this, but was rejected because of artifacts that could then possibly be introduced by small beam steering instabilities in conjunction with the off-axis position of the reference detector. Thus these asymmetries were accepted as a consequence of the applied geometry. Furthermore, it was taken into consideration that as long as these artifacts result in anti- or odd-symmetric additions to the response profiles, as was found to be the main contribution in the asymmetry in the 0.2 mm high-resolution profile of Fig. 4(a), these artifacts will have little effect on the fit parameters of the even-symmetric LSF, with even symmetric to be defined schematically as f(x)=f(−x).
Even with these estimated uncertainties taken into account, it can be seen in Figs. 4(a) and 4(b) that the modeled IC15 response profiles have lower tails than the experimental profiles. Furthermore, the 25 MV-X modeled profile has a slightly smaller width (0.3 mm FWHM) than the corresponding experimental profile. The assumptions in the model calculations, electron transport by multiple small-angle scatter only and the cutoff in electron range, are most probably the main causes for these remaining differences. An additional cause in the case of 25 MV-X is the neglect of pair creation, which has been reported to show less elongated dose kernels than Compton scatter. However, apart from these effects, the calculated IC15 response profiles, especially at 6 MV-X, agree very well with the experimental verification.

The calculated and experimental NAC response profiles agree moderately well with a difference in the FWHM of 0.4 mm. The large uncertainty in the measurements, however, does not allow for a detailed analysis of discrepancies.

The experimental diode response profiles are generally in good agreement with the calculated profiles, the difference in FWHM amounts up to 0.2 mm. This indicates that the spatial response of the diode is governed by the dimension of its sensitive element, possibly with a small contribution from the detector housing. Nevertheless, in this context it should be noted that the applied experimental geometry is ideal for diode measurements, since factors that can reportedly affect diode output, such as low-energy (scattered) photons, and directional dependence, have been minimized in the telescopic slit-beam geometry.

C. Line spread functions and penumbra broadening

The effect of reconstruction and fit of the LSFs, using Eqs. (3) and (4), on the penumbra width was assessed by a comparison of two types of detector response profiles associated with a 50 × 30 mm² primary beam: geometric addition of slit beam detector response profiles, i.e., the “real” profiles, versus the geometric addition of slit beam dose profiles convolved with reconstructed and fitted LSFs. In the latter case, with calculated LSFs, penumbra were found that were in excellent agreement to the penumbras of the “real” profiles, the largest difference was a 0.02 mm too wide penumbra for 25 MV-X. Penumbras obtained with measured LSFs were 0.3 and 0.8 mm smaller than the “real” penumbras, for 6 MV-X and 25 MV-X, respectively. Note, however, that these are worst case data, since these data apply to the steepest possible penumbras.

Another factor that was checked in the reconstruction procedure was the level of the iterative stop criterion. A stop criterion of less than 0.1% change in the squared difference of the left-hand and right-hand side of Eq. (3) yielded LSFs with higher oscillations in the central part of the curves than shown in Fig. 4, obtained with a 1% stop criterion. However, no significant difference in fitted parameters or resulting model penumbra broadening was found.

The effect of these LSFs on penumbra widths as encountered in practical situations was investigated by the calculation of the broadening of model penumbras of various steepness; Fig. 8. For both energies, 6 MV-X in Fig. 8(a) and 25 MV-X in Fig. 8(b), two experimental penumbra broadening curves are shown, based on different experimental setups. The distance between the experimental curves is indicative for the experimental uncertainty. Taking this uncertainty into account, it is concluded that the LSFs as calculated by our analytical model underestimate the penumbra broadening of an IC15 detector by approximately 0.5 mm in a 6 MV-X primary x-ray beam and by 1 mm in a 25 MV-X primary x-ray beam.

Equation (4) was directly derived from geometrical considerations. Nevertheless, it can be questioned whether the various terms are meaningful for the determination of beam penumbras of regular, macroscopic fields. This was studied by fitting the reconstructed, calculated LSF (6 MV-X) to various simplifications of Eq. (4), subsequently excluding the terms that represent the wall, central electrode, and Gaussian tail. The results, shown in Fig. 9, indicate that the wall and central electrode need not be included in the fit for this purpose, in contrast to the Gaussian tail. However, the terms that represent the wall and central electrode can become important in the deconvolution of highly modulated fields, for instance, near the thin end of a wedge.

In the literature a variety of methods have been applied to study detector-induced penumbra broadening, and several correction methods have been defined. A schematic overview of these methods is presented in Table IV, whereas results derived from the literature are marked and included in Fig. 8. Some results are discussed more extensively hereafter.

Detector size extrapolation of thimble ionization chambers in air was employed by Dawson et al., who came up with an empirical rule for primary beam penumbra broadening of 0.5 cm per centimeter internal detector size. Strictly speaking, the derived rule applies only for the studied experimental penumbra width. The results of their study in 6 MV-X and 31 MV-X beams have been indicated with points.
marked D in Figs. 8(a) and 8(b), ignoring in the latter case the difference in beam energy. As indicated in subsequent studies, the underlying assumption that detector size is the dominant factor in penumbra broadening becomes questionable at small detector sizes. The real dose penumbra width is thus expected to be larger than their extrapolated measured penumbra width. Based on another study, a difference of 0.3 mm seems a realistic estimate. The arrows in Fig. 8 indicate the direction in which the result is expected to move when considering this difference.

García-Vicente et al. concluded that a Gaussian LSF gives a better agreement between the convolved dose profile and the fitted chamber profile than an elliptic LSF. Their results might seem to be in contrast with our study, in which the elliptic term dominates the small Gaussian term in the central part of both the experiment-based LSFs and the model-based LSFs. However, the explanation for this contrast lies probably in the sensitivity of the resulting penumbra broadening for the height of the tail of the LSF profiles, as is illustrated in the difference between the experimental curves in Figs. 8(a) and 8(b), which was mainly caused by a small difference in the tail height of the response profiles, Fig. 4. From the results of our study we consider the combination of elliptic and Gaussian terms, Eq. (4), as optimal.

Charland et al. approached the determination of LSFs by using EGS4 Monte Carlo calculations for a point x-ray source in combination with measured detector profiles in a 6 MV-X 30×30 mm² beam at 15 mm depth. The penumbra broadening that they found for an IC10 detector in this way is included in Fig. 8(a) and marked with C. The best correspondence of calculations and measurements was found with an elliptic LSF with radius 4.6 mm. However, as they indicated, the finite size of the linac source is inevitably included in this LSF. The arrow in Fig. 8(a) indicates the direction in which the result will move when the source size would be taken into account.

It can be concluded that the penumbra broadening curves, Fig. 8, as derived with the experiment-based LSFs are in good agreement with the reported data, taking the in-between distance of the curves as an indication for the experimental uncertainty. While the curves were intended to assess impact and accuracy of LSFs and to allow a comparison to literature, it must be clearly noted that the curves, in contrast to the LSFs, apply only to field edges with a low out-of-field tail, such as found in practice at the depth of dose maximum. In penumbras with higher tails, the curves do no longer represent the actual penumbra broadening. Nevertheless, taking Fig. 8 as a critical example, it can be concluded that the model-based LSFs underestimate penumbra broadening by approximately up to 0.5 and 1.0 mm for 6 MV-X and 25 MV-X, respectively. This presents for a dose penumbra width of 3 mm (typically for a profile at dose maximum) an improvement of approximately 1 mm in comparison to a size-based (6 mm) LSF and typically 2 mm in comparison to the use of uncorrected IC15 profiles. A further improvement would require a better description of the tails of the LSFs, which is restricted in this analytical model by the approximations of small-angle multiple-scattering and electron range cutoff.

### D. General applicability

The present and previous study concentrate on detector response of dosimeters in a primary x-ray beam, which is clinically best comparable to the situation at dose maximum. In this section, the general applicability of the studied dosimeters, ionization chamber, diode, and diamond, also at other depths, is discussed.

The primary dose is the component with the sharpest edge and at depths of practical interest it is the dominant contribution. It can thus be hypothesized that a correction for the detector LSF of the total dose profile is a good approximation for the application of this correction on the primary dose profile only. This hypothesis was tested for the IC15 chamber by deconvolution of various calculated 6 MV-X dose profiles at depths in between 15 and 200 mm in square fields of 50 up to 200 mm size. The profiles were calculated by our treatment planning system, Helax TMS 5.1 (MDS Nordion, Canada), using IC15 measurements as basic beam data. As this treatment planning system provides a separate calculation of the primary dose, corrections applied to the total dose profile or to the primary dose component only

### Table IV. A schematic overview of studies of penumbra broadening caused by detector effects. The results of this table are included in Fig. 8 as points that are labeled according to the first column. The second column shows the corresponding literature reference numbers. Refer to the text for a more detailed discussion. Lines marked (●●) present additional measurements that were performed at dose maximum in square fields of 50, 100, and 200 mm width. The subsequent columns indicate the applied method and beam energy, the detector and the reference detector. When multiple detectors were used, the detector most similar to the IC15 chamber is included.

<table>
<thead>
<tr>
<th>Label</th>
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<th>Reference detector</th>
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</table>

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could be compared. The effect on the resulting 20%–80% penumbra width differed on average less than 0.1 mm. Therefore the important conclusion can be drawn that in practice a correction of the total measured dose profile is equivalent to a correction of the primary dose only.

Diodes, especially the unshielded types, are known to exhibit an increased response at lower energies of which the relative contribution grows with greater depths due to phantom scattering. As this energy dependence is not studied here, no general conclusions about the applicability of diode LSFs at depths beyond the dose maximum can be drawn from our study. Nevertheless, it can be stated that shielded diode measurements can provide at the depth of dose maximum a valuable check of, e.g., deconvolved ionization chamber measurements.

Diamond detectors show a direct photon response, which has been reported to contribute 27% to the detector response in a 6 MV-X macroscopic beam. The effect of this direct photon response on fictitious penumbra sharpening was assessed in the constructed macroscopic primary beam that was described in Sec. V C. In this beam, with 1.5 mm 20%–80% penumbra the diamond detector would measure 0.5 mm too little penumbra width. In this case, the magnitude of this fictitious penumbra sharpening is comparable to that was described in Sec. V C. In this beam, with 1.5 mm was assessed in the constructed macroscopic primary beam in which contributions other than primary dose are negligible, i.e., comparable to a depth of dose maximum. Shielded diode measured profiles can thus, at least at the dose maximum, be used to check LSF-deconvolved ionization chamber measurements. From this study conclusions about the use of diodes at other depths cannot be drawn.

Line spread functions have been determined and a set of model penumbra have been constructed to assess the effect of these model-based LSFs on penumbra broadening. These model penumbra have a low tail level, comparable to beam dose profiles that exist at a depth of dose maximum. At a dose penumbra with a width of 3 mm (typical for profiles at the depth of dose maximum), the model-based LSF yields a penumbra broadening of approximately 2 mm, while experimentally 2.5 mm is found in a 6 MV-X beam. In a 25 MV-X beam the corresponding figures are 2 vs 3 mm. With the readily applicable correction for the LSF, this broadening of up to 2 mm is eliminated, so that an ionization chamber like the IC15 can be well applied as a routine dosimeter in conformal radiation therapy, thus combining a well-established standard for dosimetric measurements with an accurate description of penumbra.

VI. CONCLUSIONS

The analytical model that was described in the previous study has been extended successfully to include effects of ionization chamber response in primary x-ray beams. In this extension several physical aspects have been taken into account: the electron traveling direction at the entrance surface of the detector and the corresponding expected pathlengths through the dosimeter, the replacement of medium by detector air, and the effect of the detector wall and central electrode density on the recoil of Compton electrons. The replacement of the medium by air and the presence of a wall and a central electrode were seen to affect the calculated detector response functions. A verification of these response functions with experiments in the telescopic slit geometry yields experimental detector response curves with a maximum uncertainty of ±3%, which occurs in the tails of the curves. The model-based response profiles agree with the experimental profiles to within 0.2–0.4 mm width (FWHM), depending on detector and energy.

The shielded diode was shown to require only a small size-based correction in a beam in which contributions other than primary dose are negligible, i.e., comparable to a depth of dose maximum. Shielded diode measured profiles can thus, at least at the dose maximum, be used to check LSF-deconvolved ionization chamber measurements. From this study conclusions about the use of diodes at other depths cannot be drawn.

Line spread functions have been determined and a set of model penumbra has been constructed to assess the effect of these model-based LSFs on penumbra broadening. These

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