Small Field: dosimetry in electron disequilibrium region

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Abstract. Small fields are more commonly used for radiation therapy because of the development of IMRT, stereotactic radiosurgery, and other special equipments such as Cyberknife and Tomotherapy. The dosimetry in the sub-centimeter field can result in substantial uncertainties because of the presence of electron disequilibrium due to the large dose gradients in the field. It is further complicated by the introduction of various radiation detectors, which usually perturb the conditions of disequilibrium. Hence additional corrections are required to maintain the dosimetric accuracy previously achieved for standard radiation dosimetry. A review of small field dosimetry provides some insights into the methods to characterize the detector convolution kernel and other methods to characterize detector perturbation effect.

1. Introduction

Various types of radiation detectors are used to measure relative dose distributions for therapeutic electron and photon beams. Most detectable signals from a radiation detector are correlated to the energy imparted $\delta \varepsilon$ to the detector [1]. This, in turn, is related to the absorbed dose in the detector, $D_{det}$. Table I lists types of radiation detectors, their signals, and their relationship to the dose in the sensitive volume of the detectors. The meaning of the dosimetric quantities can be found in Refs. [2-7]. In this review we will focus on the first three types of detectors, especially ionization chambers and diodes, since they are the most commonly used in acquiring beam data.

| Type               | Measured Quantities           | Relation to $D_{det}$                              |
|-------------------|-------------------------------|---------------------------------------------------|
| Ionization chambers | Charges ($Q$)                | $D_{det} = (W/e)_{air}Q/m \beta$                  |
| Si Diode detectors | Charges ($Q$)                | $D_{det} = (W/e)_{Si}Q/m \beta$                   |
| TLD               | Light intensity ($I$)        | $D_{det} \propto \int I dt$                        |
| Fricke dosimeter  | $Fe^{3+}$ content ($\Delta A$) | $D_{det} = \Delta A/\rho G_t$                     |
| Film              | Optical density ($OD$)       | $D_{det} \propto OD$                               |
| Scintillation dosimeter | Light intensity ($I$)   | $D_{det} \propto I(\lambda)$                      |
| Gel dosimeter     | Optical density change ($\Delta OD$) | $D_{det} = \Delta OD/p(\epsilon_m)G_t$            |
| Calorimetry       | Temperature ($DT$)           | $D_{det} = c_pDT$                                  |

When such a measuring device is introduced into a radiation field, it tends to disturb the field. For small field dosimetry, one major concern is the spatial resolution of the detector since the signal correlates to the integral (or mean) dose in the detector and we are interested in the dose in the
medium at one point. This correction can be done using the concept of detector convolution kernel. This is somewhat different from conditions for absolute dosimetry in large fields (> 4 cm) where the electron fluence distribution over the detector tends to be uniform (although not always possible)!

Small field dosimetry is becoming more important in radiation.[8] This review will try to be consistent with recommendation of the proposed AAPM TG155 as much as possible and focus on photon beam small field dosimetry. At the time of publication, the final report of TG155 is not yet available.

2. Perturbation factors and detector convolution kernel

The perturbation factors commonly used for absolute dosimetry can be expanded to electron disequilibrium regions using the concept of detector convolution kernel. Excellent reviews for absolute dosimetry can be found in that of Nahum [6, 9], Alm Carlsson [1], and Svensson and Brahme [10]. However, there are few papers on the perturbation factors under electron disequilibrium conditions.

If the detector is small compared to the range of the charged particles (i.e. it behaves as a Bragg cavity), one can write [9]

\[ D_{med}(P) = \bar{D}_{det} \cdot s_{med, det} \cdot p, \]  

where \( p \) is the perturbation of the electron fluence, \( s_{med, det} \) is the mass collision stopping power ratio between medium and the detector material. Note that the dose to the medium has been written as \( D_{med}(P) \) to indicate that the value required is at a specific position \( P \), which can be shifted from the center of the detector. \( \bar{D}_{det} \) is the mean dose in the detector. This expression is valid under electron disequilibrium, where \( \bar{D}_{det} \neq K_{det} \). Nahum [9] pointed out that the cause of \( p \) is the perturbation of the secondary electron fluence in the medium:

\[ p = \frac{\int (\Phi_E)/med(L_{\Delta}/\rho)_{det}dE + [(\Phi(\Delta)/med(S(\Delta)/\rho)_{det} \cdot \Delta]}{\int (\Phi_E)_{det}(L_{\Delta}/\rho)_{det}dE + [(\Phi(\Delta)_{det}(S(\Delta)/\rho)_{det} \cdot \Delta]}, \]  

where \( \Phi_E \) is the electron fluence and \( L_{\Delta}/\rho \) is the restricted stopping power ratio, all other quantities have their usual meaning [4]. For absolute dosimetry (under electron equilibrium) this perturbation factor is usually very small (a few percent) so that one can separate it into multiplication of several independent perturbation factors. This separation is not usually possible in electron disequilibrium regions where the perturbation can be much larger. One of the most common separations is the wall correction factor and displacement factor [11, 12]. The displacement (or replacement) factor is further separated into electron fluence correction and gradient correction [11]. Bjärngard and Kase [13] argue that this latter separation is non-physical because it violates Fano’s theorem [14]. MC simulation provides a general solution to quantify \( p \) for a specific dosimeter for small fields [15].

Supposing that a detector is introduced into a medium under a radiation field, the dose disturbance of the detector can be generally expressed as

\[ \bar{D}_{det} = \iiint g(r-r') \cdot D_{med}(r')dr' \]  


where \( g(r) \) is the detector convolution kernel, \( D_{\text{det}} \) is the mean dose determined by the detector, and \( D_{\text{med}} \) is the dose in the medium. Compared to Eq. (1), \( g(r) \) describes the additional dose average effect of an extended detector volume. \( g \) must have a finite range reflecting the size of the detector and the range of secondary electrons. In principle, \( g \) can include all the detector disturbance, which cannot be separated into independent effects like wall correction and displacement correction. We will not explore here how to determine \( g \) theoretically since it relates doses (or secondary electron fluences) with and without the detector and is thus extremely complicated. One could, however, try to determine \( g \) experimentally for a specific radiation quality. As a first order of approximation, Eq. (3) can be simply considered as an average of the dose distribution in the medium with a weighting function, \( g \), that depends on the detector perturbation. The convolution formalism assumes that \( g \) has the same shape everywhere within a given radiation quality.

The concept of detector convolution kernel is more useful for correcting profile measurement in regions with steep gradients because \( g \) can be independently measured. Extensive literature exists on the experimental determination of \( g \) [16-19]. All measurement techniques take advantage of the ability to modify the lateral fluence distribution of the radiation, thus \( D_{\text{med}} \). Figure 1 shows the shape of the detector convolution kernel for two thimble ionization chambers (Wellhöfer IC-10 and IC-3) and a p-type Scanditronix diode (2.5-mm diameter). These measurements were made using a 6-MV step x-ray field and the two-dimensional detector response kernels are assumed to be cylindrically symmetric. Zhu et al find that the following function fits the data best:[20]

\[
g(r) = \frac{3}{2 \pi R^2} \sqrt{1-r^2/R^2} \quad \text{for ionization chambers}
\]

\[
g(r) = \frac{1}{\pi w^2} e^{-r^2/w^2} \quad \text{for diode}
\]

The kernels are normalized using \( 2 \pi \int_0^\infty g(r) r dr = 1 \). Dawson et al found a substantial correlation between the effective radius, \( R \), and beam energy, which tends to increase with increasing photon energy [21].

![Fig. 1. Detector convolution kernel \( g(r) \) measured for Wellhöfer 0.1 cc IC-10 (solid) and 0.03 cc IC-3 (dashed) ion chambers, and a Scanditronix p-type diode (dash-dotted).]

A general formalism [22] for small field absolute dosimetry uses Eq. 1 in a similar way as that used for a broad beam using AAPM TG-51 [12] or IAEA TRS-398 [23], but is modified to use a machine specific reference field (if 10x10 cm\(^2\) field is not available) [24]. The ratio of doses between the clinical field to the reference field at the reference depth is termed output ratio in water. Output ratio in water can be separated into output ratio in air and phantom scatter factor.[25] Studies have shown a difference between the true output ratios (e.g., MC generated) and those measured using a specific dosimeter [22, 26-32]. Limited studies quantify this field size dependent correction factor for various...
dosimeters by MC simulation.[8] Similarly TMR/OAR for small fields can deviate from those measured using a dosimeter if the detector size is too large.[8, 33] These differences can be explained by the detector convolution method (Eq. 3), which account for the effects caused by the lack of CPE and the penumbra effect due to obscuring the x-ray source.

3. Depth dose measurements

3.1 Buildup region

The golden standard for dose measurements in the buildup region is the extrapolation parallel-plate chamber. However, these measurements are time consuming. Silicon diodes with small active volume in the radiation direction has been found to have little perturbation effect [34, 35]. Without special correction, a thimble-type ionization chamber overestimates the dose in the buildup region because of its relatively large volume.

A parallel-plate chamber with fixed plate separation can also be used to measure the depth dose in the buildup region. However, correction is needed for the fixed plate separation. Velkley et al studied the relationship between the correction factor and plate separation for an extrapolation parallel-plate chamber at different depths and photon energies. They found that the parallel-plate chamber with fixed plate separation tends to overestimate dose in the buildup region [36]. They were the first to introduce a correction factor \( \xi \) in the form of [36]

\[
P'(d) = P(d) - \xi(E,d/d_{max}) \times l,
\]

where \( l \) is plate separation, \( d \) is depth to front surface of chamber, \( P' \) is corrected percentage buildup, and \( P \) is the percentage buildup obtained with chamber with plate separation \( l \). \( \xi \) decreases with increasing photon energy and increasing depth for a fixed photon energy. For their particular extrapolation chamber design, Velkley et al found \( \xi \) to be 4.5%/mm, 3%/mm, 1.6%/mm, and 1%/mm for \( ^{60}\text{Co}, 4\text{MV}, 8\text{MV}, \) and 25MV, respectively, on the surface.

Nilsson and Montelius [37] performed one of the most extensive studies of the fluence perturbation of parallel-plate ionization chamber under electron disequilibrium conditions and concluded that it is not possible to correct the perturbation effect in one parallel-plate chamber with fixed plate separation with correction factors obtained with extrapolation chambers of other dimensions. Monte Carlo simulation for parallel-plate chamber perturbation effect has been performed but only for depths beyond \( d_{max} \) [38]. Correction factors \( \xi \) for specific chambers have been experimentally determined by Mellenberg [39] for the Markus chamber (PTW 30-329), Gerbi [40] for the Attix chamber, and Gerbi and Khan [41] for a range of commercially available fixed-separation parallel-plate chambers (Capintec PS-033, the PTW 30-329 Markus chamber, and Memorial chambers with circular or rectangular electrodes). Gerbi and Khan [41] concluded that the Velkley correction (Eq. (5)) produces acceptable results (within 2%) for all chambers but the Marcus chamber, because of its small guard, is still on average 11%, 6%, and 3.7% too high after correction for \( ^{60}\text{Co}, 6\text{MV}, \) and 10MV photon energies, respectively. Rawlison et al reviewed Velkley correction factors for commercially available parallel-plate chambers and pointed out that Velkley’s formula needs to be modified to include influence of the chamber geometry and density of wall material [42]. They provided an improved formula:

\[
P'(d) = P(d) - c(E) \cdot (l/w) \cdot \rho^0.8 \cdot e^{-0.8d/d_{max}}
\]

where \( w \) is the inner diameter of wall, \( \rho \) is density of wall material (g/cm\(^3\)), \( c(E) = 43\%, \, 27\%, \, 15\% \) for Co-60, 6MV, 18MV, respectively. All other parameters are the same as Eq. (5). This modified
equation works well even with the Markus chamber. Gerbi and Kahn [43] also examined chamber response in the buildup region for obliquely incident photon beams and found that the overresponse also changes with incident angle. They recommend using an extrapolation chamber or a well-guarded fixed-separation plane-parallel ionization chamber with a plate separation of 1 mm or less. Another important correction factor for parallel-plate ionization chamber is the polarity effect, which can be easily corrected by averaging the charges for both polarities. Several references discuss its origin [44-47] Gerbi and Kahn [48] and Aget and Rosenwald [45] give the polarity effect for several commercially available chambers for photon and electron beams. Diode is found to be a good detector for PDD measurement due to its small detector size.[35]

3.2 TMR/PDD measurements beyond buildup region

The major difference between PDD for small field and that for conventional field size is the effect caused by the change field profile vs. depth. As a result, the measured PDD may be different from the true PDD due to the increasing field width vs. increasing depth for a fixed SSD (Eq. 1). To remedy that, a simpler method is to measure TMR directly with the detector centered on the isocenter.[49] The variation of stopping power ratio vs. depth is found to be small for small fields.[8, 50, 51]

4. Small field profile measurements

Artificial broadening caused by the detector size is illustrated in Fig. 2, taken from Ref. [16]. Dawson et al studied the relation between penumbra width and ionization chamber inner diameter for a series of specially designed chambers with inside diameter varying between 0.3 to 1.4 cm [21]. They concluded that the P20-80 or P10-90 penumbral degradation associated with the inside diameter of the chamber can be corrected using a standard slope of 0.5 cm/cm inside diameter, regardless of the chamber type and radiation quality. Metcalfe et al [52] compared penumbra measured with ionization chambers, TLD, Scanditronix diode, and film and concluded that the diode (2.5 mm diameter) gives result consistent with film and very closely (within 0.2 mm) models the response of a point detector. TLD (1×1×6 mm) gives better result. We have tested a new 0.03 cm³ ionization chamber (Wellhöfer IC-3 with 4-mm inner diameter) for penumbra measurement and found the result agrees with diode to within 0.5 mm.

Fig. 2. Penumbra for a 6 MV x-ray beam obtained with 9.5 mm (dotted) and 5.8 mm (dashed) inner diameter ionization chamber. Full curve is measured with film. Taken from Ref. [16].

Existing studies have proven definitively that the detector convolution kernel can explain the broadening of the measured penumbra due to the detector size [16-19, 21, 53]. It is possible to extrapolate the true penumbra using the detector convolution kernel. However, the current deconvolution algorithm is very susceptible to noise and requires manual tuning to eliminate the noise effect [18]. This problem should be solvable if both the penumbra and detector convolution kernel are expressed as analytical functions. Several studies give various analytical expressions for the penumbra [52, 54] and the detector convolution kernel (Eq. (4)).
5. Small field output measurements

For output characterization of stereotactic cones, detector convolution kernel can still be used, one has to consider the effect in two-dimensions. Because the penumbra for small field may cut into the central-axis, the output can also decrease as a result. These effects can be expressed using detector convolution kernel as [20]

\[
F(x, y) = \int \int g(x - x', y - y') \cdot f(x', y') dx' dy',
\]

(7)

where \(F(x,y)\) is the measured profile, \(f(x,y)\) is the true profile, and \(g\) is the detector convolution kernel. On the central-axis, the reduction of output factor, \(CF\), can be expressed as [20]

\[
CF = F(0,0) = \int \int g(x', y') \cdot f(x', y') dx' dy'.
\]

(8)

Figure 3 compares calculated and measured correction factors for ionization chambers with detector convolution kernel described in Fig. 1. Here we have assumed that both \(g\) and \(f\) are cylindrically symmetric, i.e., they are a function of \(\sqrt{x^2 + y^2}\). Deconvolution for Eq. (7) with cylindrical symmetry can be performed using inverse Abel transform. [55]

Several studies have been performed to compare the output factors measured for the stereotactic cones by various detectors [8, 49, 56-58]. Table 2 lists the results for relative output factors for a 6MV x-rays from a Clinac 2500 accelerator [49]. Serago et al [49] concluded that small diode and TLD seem to be the appropriate choices of radiation detectors to determine relative dose for small field sizes. Bjärngard et al performed Monte-Carlo simulation and found the diode detector breakdown for cone diameter less than 0.5-cm [56].

One of key procedure to develop the correction factor for small field is an reliable algorithm to perform deconvolution. Several recent studies have provide effective method to perform such task while achieve reasonable uncertainties. [59, 60]

Table 2: Relative output factors for 6 MV x-rays measured with ionization chamber (IC), diode, TLD, and film
6. Concluding Remarks

The perturbation factor $p$ for detectors has only been vigorously studied for electron beams and for photon beams under the condition of transient charged particle equilibrium, not suitable for small field dosimetry. These studies are mostly done for ionization chambers. More importantly, these conditions restrict the electron fluence distribution to be uniform across the detector. The detector convolution kernel expanded this to regions where electron fluence distribution is not uniform. However, substantial works remains to understand the beam quality dependence of the detector convolution kernel and more theoretical work such as Monte-Carlo simulation is needed to understand the origin of dosimetry uncertainties.

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