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研究速報

## A Theoretical Study of Measuring In-Air Collision Kerma

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### 空中衝突カーマの測定に関する理論的研究

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#### Introduction

Attix<sup>1)~3)</sup> has introduced the concept of collision kerma, and Khan *et al.*<sup>4)</sup> have proposed a revised scatter-maximum ratio (SMR) concept. Iwasaki has developed the relationship<sup>5)</sup> between primary collision kerma and zero-area tissue-maximum ratio (TMR), and the relationship<sup>6)</sup> between primary collision kerma and revised SMR. However, there is no strict method of measuring the in-air collision kerma for photons whose energy is higher than about 3 MeV. The in-air collision kerma is important when calculating primary and scatter dose based on the primary collision kerma in a medium. In this paper, a theoretical study of measuring the in-air collision kerma for high-energy photon beams will be described.

#### Theoretical Considerations

An ionization chamber may be calibrated in terms of the quantity  $N_{\text{gas}}$ , called the cavity-gas calibration factor<sup>7)</sup>. Attix<sup>8)</sup> has derived the equation relating  $N_{\text{gas}}$  to the exposure calibration factor,  $N_x$ , by a clearer method than that given in the AAPM protocol<sup>7)</sup>. The Attix derivation considers the collision kerma and absorbed dose in an imaginary infinitesimal mass of wall material placed both at the center of the chamber and at the same point in free air. However, he does not clearly describe what material should be used for the imaginary infinitesimal mass. Usually the chamber wall is constructed of several different materials. Here let the central electrode be a part of chamber wall. The Attix  $N_{\text{gas}}$  equation intimates that the chamber wall is made of water-like materials. It can easily be understood that any material may be used for the *imaginary infinitesimal* mass. In this paper we propose to use water. The reason is that some physically important quantities can be expressed more simply. Moreover, we propose to use a buildup cap made of arbitrary materials, including aluminum, copper, lead, etc. Equation (8) in Ref. 8 may then be rewritten as

$$N_{\text{gas}} = N_x (W/e)_{\text{air}} (\mu_{\text{en}}/\rho)_{\text{wat,air}} A_{\text{ion}} A_{\text{wall}} (L/\rho)_{\text{gas,wat}}, \quad (1)$$

where  $N_x$  is the exposure calibration factor uncorrected for ion recombination;  $(W/e)_{\text{air}}$  is the mean energy expended per unit charge in dry air;  $(\mu_{\text{en}}/\rho)_{\text{wat,air}}$  is the ratio of mass energy-absorption coefficients for water/air(dry), evaluated for the photon spectrum present, usually  $^{60}\text{Co}$   $\gamma$ -rays;  $A_{\text{ion}}$  is the ion-collection

efficiency at calibration;  $A_{\text{wall}}$  is the wall correction factor, including the effects of electron transport, defined<sup>9)</sup> as the ratio of the mean absorbed dose in an imaginary infinitesimal mass of water in the cavity to the water collision kerma in free air;  $(L/\rho)_{\text{gas, wat}}$  is the ratio of restricted stopping powers for gas/water, evaluated for the electrons crossing the cavity.

Next, we refer to a practical method of obtaining the value of  $A_{\text{wall}}$ , where we use such a chamber as the Capintec-Farmer 0.6-cm<sup>3</sup> chamber (the inherent wall surrounding the cavity is approximately water-equivalent), the beam may be of arbitrary high energy, and the materials and thickness of the buildup cap may be chosen arbitrarily (the chamber reading should not reflect electron contamination from the air and the irradiation head). Here we assume that dose and kerma measurements are performed at a constant distance from the source on the beam axis, that fields are circular and measured at the constant distance, and that the dose and kerma measuring points coincide with the center of the chamber.

Let  $K_0$  be the ratio of the incident water collision kerma in free air to the maximum primary dose at depth  $z_{\text{max}}$  in a semi-infinite water phantom, where the primary dose is under the condition of lateral electronic equilibrium. Consider an irradiation that makes a maximum primary dose of  $D_p(z_{\text{max}}, r)$  in a semi-infinite water phantom, where  $r$  is the field radius. If the chamber is set in free air with a buildup cap, then the mean absorbed dose in an imaginary infinitesimal mass of water in the cavity is

$$D_{\text{air}}(r) = K_0 A_{\text{wall}} D_p(z_{\text{max}}, r). \quad (2)$$

On the other hand, the dose at depth  $z$  in a semi-infinite water phantom is

$$D(z, r) = [\text{TMR}(z, 0) + \text{SMR}(z, r)] D_p(z_{\text{max}}, r), \quad (3)$$

where  $\text{TMR}(z, 0)$  is the zero-area tissue-maximum ratio in water [ $\text{TMR}(z_{\text{max}}, 0) = 1$ ], and  $\text{SMR}(z, r)$  is the scatter-maximum ratio in water revised by Khan *et al.*<sup>4)</sup>, expressing the ratio of the scatter dose at  $z$  to the primary dose at  $z_{\text{max}}$ . Therefore, the tissue-air ratio (TAR) at depth  $z$  may be expressed as

$$\begin{aligned} \text{TAR}(z, r) &= D(z, r) / D_{\text{air}}(r) \\ &= [\text{TMR}(z, 0) + \text{SMR}(z, r)] (K_0 A_{\text{wall}})^{-1}. \end{aligned} \quad (4)$$

On the assumption that the primary photon spectrum does not change with depth, Iwasaki<sup>5)</sup> has developed a method of constructing a zero-area TMR functional equation. Figure 3 in a paper by Bagne<sup>10)</sup> indicates that 4, 10, 25, and 45 MeV peak energy x rays can satisfy the above assumption very well. The zero-area TMR can then be expressed<sup>5)6)</sup> as

$$\text{TMR}(z, 0) = T_0 \exp(-\mu z) - (T_0 - C_0) \exp(-az) + U_0 \exp(-bz), \quad (5)$$

where  $T_0$ ,  $C_0$ ,  $U_0$ ,  $a$ ,  $b$ , and  $\mu$  (attenuation coefficient of water for primary photons) are constants. The values of  $U_0$ ,  $a$ , and  $b$  can be determined after setting values for  $T_0$ ,  $C_0$ , and  $\mu$ , where usually we can put  $C_0 = -100$ . For convenience, let the value of  $T_0$  be the maximum that can satisfy  $\text{TMR}(0, 0) = D_s$ ,  $\text{TMR}(z_{\text{max}}, 0) = 1$ , and  $d\text{TMR}(z_{\text{max}}, 0)/dz = 0$ . Such a value of  $T_0$  can make the ratio of primary dose to primary collision kerma be a continuous increasing function with depth. The value of  $K_0$  can also be derived simultaneously<sup>5)</sup>. The values of  $z_{\text{max}}$  and  $D_s [= \text{TMR}(0, 0)]$  can be obtained by extrapolation using data of large fields<sup>11)12)</sup>, and the value of  $\mu$  can be obtained by measuring the narrow-beam attenuation curve for water<sup>13)</sup>.

Let  $M(z, r)$  and  $M_{\text{air}}(r)$  be the chamber readings for  $D(z, r)$  and  $D_{\text{air}}(r)$ , respectively, where  $M(z, r)$  and  $M_{\text{air}}(r)$  should be obtained without and with the buildup cap, respectively, and should be corrected for cavity-gas temperature and pressure, ion-collection efficiency, etc. Exact determination of  $\text{TAR}(z, r)$  in Eq. (4) requires that  $D(z, r)$  be interpreted from measured  $M(z, r)$  by using Eq. (9) in Ref. 7, and that  $D_{\text{air}}(r)$  be interpreted from measured  $M_{\text{air}}(r)$  using Eqs. (2) and (5) in the reference. This, of course, means that the

various factors have to be known. On the other hand, TAR and SMR data are usually made using relative chamber readings. Therefore, we may assume

$$M(z, r)/M_{\text{air}}(r)=D(z, r)/D_{\text{air}}(r). \quad (6)$$

Accordingly, the value of  $A_{\text{wall}}$  can be derived from Eqs. (4) and (6). For in-water dose measurements, it is desirable that the central electrode be made of water-like materials.

On referring to Eqs. (2) and (5) in Ref. 7, the water collision kerma ( $K_{\text{air}}$ ) at a point in free air on and off the beam axis may be measured using the equation

$$K_{\text{air}}=M_{\text{air}}N_{\text{gas}}(L/\rho)_{\text{wat,gas}}/A_{\text{wall}}, \quad (7)$$

where  $M_{\text{air}}$  is the chamber reading at the point in free air with the buildup cap, corrected for cavity-gas temperature and pressure, ion-collection efficiency, etc. If the buildup cap is made of high-density materials, then the size of the detector can be small so that a precise distribution of incident water collision kerma can be produced.

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