The Ion Collection Efficiency of an Ionization Chamber in Pulsed Radiation

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The accuracy of Boag’s formula and two-voltage technique for determining the ion collection efficiency of an ionization chamber exposed to high-intensity pulsed radiation is examined. Results with these methods were compared to the experimental ion collection efficiencies estimated with the saturation charge by graphical extrapolation. When the influence of the space charge can be ignored, results with the two-voltage technique show much better agreement with the experimental values. Results with Boag’s formula give a discrepancy between the experimental values at high charge density because an unreliable value (nominal value) is used for the effective electrode spacing of the ionization chamber. Therefore, we investigated the effect of the effective electrode spacing for real ionization chamber estimated with the two-voltage technique. We found that the results with Boag’s formula using the estimated effective electrode spacing agree much better with the experimental values even at high charge density.

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1. INTRODUCTION

An ionization chamber has been used widely for measuring the absorbed dose under irradiation of high-energy photon and electron beams. In these cases, there is a problem in effect of the ion recombination loss. Especially, it is difficult to collect all the ionized ions even with high collecting voltage in the measurement of high-intensity pulsed radiation.

A theoretical formula for obtaining the ion collection efficiency is given first by Boag.\(^1\) This formula can be approximated by using the collected charge density, the electrode spacing and collecting voltage in the ionization chamber. However, it is not easy to obtain the accurate electrode spacing for real ionization chambers. Boag and Currant\(^3\) proposed a method called “two-voltage tech-
nique" to determine the ion collection efficiency when the exact value of the electrode spacing is not known. Boag's formula [Eq. (4) in this report] and the two-voltage technique are useful methods\(^3-^6\) to determine the usual ion collection efficiency. However, there are reports\(^7-^8\) in which these methods produce a discrepancy between the normal value for high-intensity pulsed radiation.

In this paper, the accuracy of the method using the Boag's formula and the two-voltage technique is examined for use of high-intensity pulsed x-ray and electron beams produced by electron linear accelerator for medical use. Also, the usefulness of Boag's formula using the effective electrode spacing estimated with the two-voltage technique for real ionization chamber is presented.

2. THEORY

2.1. Boag's formula

The formula for the ion collection efficiency, \(f\), for pulsed radiation is given by Boag\(^1\) as follows:

\[
f = \frac{1}{\mu} \ln(1 + u),
\]

(1)

\[
u = \frac{\mu r d^2}{V},
\]

(2)

\[
\mu = \frac{a/e}{(k_+ + k_-)},
\]

(3)

where \(a\) is the ion recombination coefficient, \(e\) is the unit charge, \(k_+\) and \(k_-\) are the mobilities of the positive and negative ions, respectively, while \(r\) is the initial charge density of the positive and negative ions created by the pulse, \(d\) is the effective electrode spacing (for parallel-plate chambers, this corresponds to the actual electrode spacing, but for cylindrical or spherical chambers, the equivalent spacing must be calculated) and \(V\) is the collecting voltage.

2.2. Approximation of Boag's formula

Since it is difficult to measure \(r\) directly, it is convenient to express the ion collection efficiency, \(f\), in terms of the charge density which is collected per pulse, \(p\) (\(\phi = f \cdot r\)). The ion collection efficiency is expressed by

\[
f = \nu(\exp(\nu) - 1),
\]

(4)

where

\[
\nu = \frac{\mu p d^2}{V}.
\]

(5)
The value $\mu$ is equal to $3.00 \times 10^{10} \text{ VmC}^{-1}$ and $p$ can be approximated from the product of the value measured by the ionization chamber, $Q$, and $^{60}\text{Co}$ exposure calibration factor, $N_c$. And $p$ is defined by

$$p = \rho_{\text{air}} N_c Q / (t \cdot pps),$$

where $\rho_{\text{air}}$ is the atmospheric density (1.197 kg m$^{-3}$, 22 $^\circ$C, 101.33 kPa), $t$ is exposure time, $pps$ is the number of pulses per second. The equivalent electrode separation of a cylindrical chamber can be calculated as

$$d_{\text{cyl}} = (a-b) \left\{ \ln(a/b) / \ln(2) \right\}^{1/2},$$

where $a$ is the internal radius of the outer electrode and $b$ is the external radius of the inner electrode.

### 2.3. Two-voltage technique

Boag and Currant$^2$ showed that when the charges collected at different voltages $V_1$ and $V_2$ are $Q_1$ and $Q_2$, respectively, the charge ratio $Q_1/Q_2$ is obtained from Eqs. (1) and (2):

$$Q_1/Q_2 = (V_1/V_2) \ln(1+u_1) / \ln(1+u_1V_1/V_2).$$

Thus, Eq. (8) can be solved for $u_1$. The ion collection efficiency $f_1$ at $V_1$ can be obtained by putting $u_1$ back into Eq. (1).

Casson$^10$ obtained an equation using a polynomial approximation that covers the actual voltage region:

$$f_1 = 1 - ax - bx^2,$$

where

$$a = (V_1/V_2 - 1)^{-1},$$

$$b = (V_1/3V_2) (V_1/V_2 - 1)^{-2},$$

$$x = Q_1/Q_2 - 1.$$

### 2.4. Graphical method$^{11}$

Since the expansion of $\exp(v)$ in Eq. (4) be simplified in case of $v \ll 1$, the ion collection efficien-
cy can be approximated as follows:

\[ f = Q / Q_0 = 1/[1 + (1/2) v^2] \]

where \( Q_0 \) is the saturation charge. Therefore, from Eq. (5),

\[ Q_0 \approx Q[1+(1/2)\mu d^2/V] = Q[1 + \text{const.} \langle \phi/V \rangle] \]

Namely, the value of the saturation charge is given in the graph to extrapolate \( 1/V \) to zero.

3. INSTRUMENTS AND METHODS

The experimental measurements were carried out using 10 MV x-rays, 10 MeV and 15 MeV electrons with several radiation density produced by a Mitsubishi linear accelerator ML-15 M III. The pulse length was 5 \( \mu \)s and the repetition frequency was 44 pulses \( s^{-1} \) for a dose rate of 250 cGy min\(^{-1}\) in 10 MV x-rays, while it was 2 \( \mu \)s and 28 pulses \( s^{-1} \) for a dose rate of 400 cGy min\(^{-1}\) in 10 MeV electrons, and 2 \( \mu \)s and 14 pulses \( s^{-1} \) for a dose rate of 400 cGy min\(^{-1}\) in 15 MeV electrons. The exposure time was 48 seconds for 10 MV x-rays, and 30 seconds for electron beams, respectively. The collected charge was measured at a depth of 5 cm in a Mix-DP phantom and with a source–chamber distance of 90 cm for 10 MV x-rays, and it was measured at a depth of the peak dose with a source–surface distance of 100 cm as for electron beams.

An ionization chamber of the PTW–N30001 (Physikalisch–Technische Werkstätten, Freiburg, Germany) 0.6 cm\(^3\) Farmer–type was used. The internal radius of the outer electrode and the external radius of the inner electrode of the chamber were nominally \( a = 3.05 \) mm and \( b = 0.5 \) mm, respectively. The electrometer of the RAMTEC 1000 Dose–Dose Rate Meter (Toyo Medic Co., Ltd., Osaka, Japan) which can be varied arbitrarily from 20 V to 500 V was used. The collected charge was measured at 50 different steps from 50 V to 500 V. The \(^{60}\)Co exposure calibration factor for the chamber was \( 1.430 \times 10^{-3} \) C kg\(^{-1}\) nC\(^{-1}\).

The ion collection efficiencies obtained from Eq. (4), and from Eqs. (1) and (9) for the two–voltage technique, were compared to those estimated with the saturation charge by graphical extrapolation. Equation (1) was calculated using the value of \( u_1 \) obtained from Eq. (8). The voltage ratios used in the two–voltage technique were up to the value of 10.

4. RESULTS OF ANALYSIS

The collected charge \( Q \) is plotted versus the reciprocal of the collecting voltage as shown in Fig. 1. The saturation charge \( Q_0 \) was obtained from a more rigorous nonlinear curve–fitting value of the correlation factor, 0.9999. The resultant values were 44.70 nC for 10 MV x–rays, 41.30 nC for 10 MeV electrons, and 41.37 nC for 15 MeV electrons, respectively.

The saturation curves obtained from the values of the ion collection efficiency, \( f = Q/Q_0 \), are
presented in Fig. 2. The ion collection efficiencies at 500 V were about 0.99 for 10 MV x-rays, 0.98 for 10 MeV electrons, and 0.97 for 15 MeV electrons, respectively. The initial charge density of ions created by the pulse was calculated by inserting $Q_0$ instead of $Q$ in Eq. (6):

$$r = \rho_{sat} N_c Q_0 / (t \cdot pps).$$

The calculated values of $r$ were $3.59 \times 10^{-5}$ Cm$^{-3}$ pulse$^{-1}$ for 10 MV x-rays, $8.38 \times 10^{-5}$ Cm$^{-3}$ pulse$^{-1}$ for 10 MeV electrons, and $1.69 \times 10^{-4}$ Cm$^{-3}$ pulse$^{-1}$ for 15 MeV electrons, respectively.

The ion collection efficiencies obtained from Eq. (4), and from Eqs. (1) and (9) for the two-voltage technique, were compared to the values of the experimental ion collection efficiency, $f_1 = Q_1/Q_0$, obtained from the saturation charge $Q_0$ and the collected charge $Q_1$ at $V_1$ in Table 1, 2, and 3, respectively. In Table 1 and 2, the results with Eqs. (1) and (9) show much better agreement with the values of $f_1 = Q_1/Q_0$. Equation (4) has slightly larger errors than the two-voltage technique, and shows tendency that the errors increase at low voltage. From Table 3, it is known that the two-voltage technique gives some errors, and it gives larger errors at low voltage of $V_1=50$ V even when combined with the highest value of $V_1=500$ V. Also, compared to the values of $f_1 = Q_1/Q_0$, results with Eq. (4) show rather large errors, and the errors increase as the collecting voltage decreases.
5. DISCUSSION

The results with Eqs. (1) and (9) for the two-voltage technique show good agreements with the experimental ion collection efficiencies obtained from the saturation charge compared to those with Eq. (4). However, for high charge density of \( r = 1.69 \times 10^4 \text{ Cm}^{-3} \text{ pulse}^{-1} \), this method has some errors. This may result from the influence of voltage drop because of the screening effect of the space charge.\(^7\,^{12}\,^{13}\) The influence of the space charge is represented remarkably at low voltage of \( V_2 = 50 \text{ V} \).

\[ \text{Table 1. Comparison of ion collection efficiencies obtained using various analytical methods at a value of } r = 3.59 \times 10^{-5} \text{ Cm}^{-3} \text{ pulse}^{-1} (10 \text{ MV x-rays}). \]

<table>
<thead>
<tr>
<th>( V )</th>
<th>( Q_1 ) (nC)</th>
<th>( V_1 )</th>
<th>( Q_1 ) (nC)</th>
<th>Eq. (1)</th>
<th>% error</th>
<th>Eq. (9)</th>
<th>% error</th>
<th>Eq. (4)</th>
<th>% error</th>
<th>( Q ) ( = 44.70 \text{ nC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>44.03</td>
<td>250</td>
<td>44.03</td>
<td>0.9921</td>
<td>-0.06</td>
<td>0.9921</td>
<td>-0.06</td>
<td>0.9913</td>
<td>-0.14</td>
<td>0.9927</td>
</tr>
<tr>
<td>200</td>
<td>43.86</td>
<td>150</td>
<td>43.61</td>
<td>0.9924</td>
<td>-0.03</td>
<td>0.9924</td>
<td>-0.03</td>
<td>0.9924</td>
<td>-0.03</td>
<td>0.9927</td>
</tr>
<tr>
<td>100</td>
<td>43.11</td>
<td>50</td>
<td>41.63</td>
<td>0.9925</td>
<td>-0.02</td>
<td>0.9925</td>
<td>-0.02</td>
<td>0.9925</td>
<td>-0.02</td>
<td>0.9927</td>
</tr>
</tbody>
</table>

| 400 | 44.28          | 200 | 43.86          | 0.9906 | 0.01   | 0.9905 | 0.01   | 0.9905 | 0.01   | 0.9905               |
| 150 | 43.61          | 100 | 43.11          | 0.9907 | 0.02   | 0.9907 | 0.02   | 0.9907 | 0.02   | 0.9907               |
| 50  | 41.63          | 50  | 41.63          | 0.9907 | 0.02   | 0.9907 | 0.02   | 0.9907 | 0.02   | 0.9907               |

| 300 | 44.15          | 150 | 43.61          | 0.9876 | 0      | 0.9876 | 0      | 0.9876 | 0      | 0.9876               |
| 100 | 43.11          | 50  | 41.63          | 0.9878 | 0.02   | 0.9878 | 0.02   | 0.9878 | 0.02   | 0.9878               |
| 50  | 41.63          | 100 | 43.11          | 0.9878 | 0.02   | 0.9878 | 0.02   | 0.9878 | 0.02   | 0.9878               |

| 200 | 43.86          | 100 | 43.11          | 0.9823 | 0.11   | 0.9823 | 0.11   | 0.9823 | 0.11   | 0.9823               |
| 50  | 41.63          | 50  | 41.63          | 0.9817 | 0.05   | 0.9817 | 0.05   | 0.9817 | 0.05   | 0.9817               |

| 100 | 43.11          | 50  | 41.63          | 0.9836 | 0.07   | 0.9836 | 0.07   | 0.9836 | 0.07   | 0.9836               |
| 50  | 41.63          | 100 | 43.11          | 0.9836 | 0.07   | 0.9836 | 0.07   | 0.9836 | 0.07   | 0.9836               |

* Equation (4) is calculated from the effective electrode spacing, \( d_{\text{mean}} \), obtained by Eq. (7).

\[ \text{Table 2. Comparison of ion collection efficiencies obtained using various analytical methods at a value of } r = 8.38 \times 10^{-5} \text{ Cm}^{-3} \text{ pulse}^{-1} (10 \text{ MeV electrons}). \]

<table>
<thead>
<tr>
<th>( V )</th>
<th>( Q_1 ) (nC)</th>
<th>( V_1 )</th>
<th>( Q_1 ) (nC)</th>
<th>Eq. (1)</th>
<th>% error</th>
<th>Eq. (9)</th>
<th>% error</th>
<th>Eq. (4)</th>
<th>% error</th>
<th>( Q ) ( = 41.30 \text{ nC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>40.60</td>
<td>250</td>
<td>39.83</td>
<td>0.9605</td>
<td>-0.26</td>
<td>0.9604</td>
<td>-0.27</td>
<td>0.9799</td>
<td>-0.33</td>
<td>0.9831</td>
</tr>
<tr>
<td>200</td>
<td>39.56</td>
<td>150</td>
<td>39.05</td>
<td>0.9621</td>
<td>-0.10</td>
<td>0.9622</td>
<td>-0.09</td>
<td>0.9622</td>
<td>-0.09</td>
<td>0.9622</td>
</tr>
<tr>
<td>100</td>
<td>39.97</td>
<td>50</td>
<td>35.21</td>
<td>0.9820</td>
<td>-0.11</td>
<td>0.9820</td>
<td>-0.11</td>
<td>0.9820</td>
<td>-0.11</td>
<td>0.9820</td>
</tr>
</tbody>
</table>

| 400 | 40.41          | 200 | 39.56          | 0.9781 | -0.04  | 0.9781 | -0.04  | 0.9751 | -0.35  | 0.9785               |
| 150 | 39.05          | 100 | 37.97          | 0.9822 | -0.09  | 0.9822 | -0.09  | 0.9822 | -0.09  | 0.9822               |
| 50  | 35.21          | 50  | 35.21          | 0.9777 | -0.08  | 0.9777 | -0.08  | 0.9777 | -0.08  | 0.9777               |

| 300 | 40.08          | 150 | 39.05          | 0.9730 | 0.26   | 0.9731 | 0.27   | 0.9671 | -0.35  | 0.9705               |
| 100 | 37.97          | 100 | 37.97          | 0.9714 | 0.09   | 0.9714 | 0.09   | 0.9714 | 0.09   | 0.9714               |
| 50  | 35.21          | 50  | 35.21          | 0.9709 | 0.04   | 0.9709 | 0.04   | 0.9709 | 0.04   | 0.9709               |

| 200 | 39.56          | 100 | 37.97          | 0.9570 | -0.09  | 0.9570 | -0.09  | 0.9570 | -0.09  | 0.9570               |
| 50  | 35.21          | 100 | 35.21          | 0.9566 | -0.14  | 0.9566 | -0.14  | 0.9566 | -0.14  | 0.9566               |

| 100 | 37.97          | 50  | 35.21          | 0.9175 | -0.21  | 0.9175 | -0.21  | 0.9175 | -0.21  | 0.9175               |
| 50  | 35.21          | 100 | 35.21          | 0.8849 | -2.08  | 0.8849 | -2.08  | 0.8849 | -2.08  | 0.8849               |

* Equation (4) is calculated from the effective electrode spacing, \( d_{\text{mean}} \), obtained by Eq. (7).

5. DISCUSSION

The results with Eqs. (1) and (9) for the two-voltage technique show good agreements with the experimental ion collection efficiencies obtained from the saturation charge compared to those with Eq. (4). However, for high charge density of \( r = 1.69 \times 10^{-4} \text{ Cm}^{-3} \text{ pulse}^{-1} \), this method has some errors. This may result from the influence of voltage drop because of the screening effect of the space charge.\(^7\,^{12}\,^{13}\) The influence of the space charge is represented remarkably at low voltage of \( V_2 = 50 \text{ V} \).
In our experimental results, the appropriate voltage ratio $V_1/V_2$ was larger than 2.0 or 2.5. The value of $V_1/V_2$ should be at least larger than 2.0 to reduce experimental errors.\(^5\)\(^7\) However, $V_2$ must not be so low because the space charge seriously affects $Q_2$ at high charge density.

On the other hand, the results with Eq. (4) have larger errors as the charge density increases. This is because the effective electrode spacing of an ionization chamber calculated from Eq. (7) differs from the actual value. Therefore, it is effective to calculate the actual effective electrode spacing by means of the two-voltage technique.

At $r = 3.59 \times 10^{-5}$ Cm\(^{-3}\) pulse\(^{-1}\), the two-voltage technique gives much better results with the accuracy of 0.1% to the values of $f_i = Q_i/Q_0$. Accordingly, at $r = 3.59 \times 10^{-5}$ Cm\(^{-3}\) pulse\(^{-1}\), the actual effective electrode spacing was estimated with $u_1 = \mu d_{cyt}/V_1$ using the value of $u_1$ obtained from Eq. (8). The $\mu$ value is $3.0 \times 10^{10}$. The value of $d_{cyt}$ was estimated to be 2.65 mm. This value has a difference of about 0.2 mm to the nominal value 2.86 mm \([d_{cyt, nom}]\) calculated from Eq. (7).

The ion collection efficiencies recalculated from Eq. (4) using $d_{cyt(two)} = 2.65$ mm estimated with the two-voltage technique, that is, results calculated using $d_{cyt(two)}$ are presented in Table 4. They agree much better with the values of $f_i = Q_i/Q_0$ at any charge density. At high charge density of $r = 1.69 \times 10^{-4}$ Cm\(^{-3}\) pulse\(^{-1}\), they produce smaller errors rather than those with the two-voltage technique except for low voltage region. Thus these results show that the actual effective electrode spacing estimated with the two-voltage technique is reliable.

Equation (4) using $d_{cyt(two)}$ gives errors as shown in Table 4 when the ion collection efficiency is less than 0.90. This may result from the influence of the space charge.\(^7\)\(^12\)\(^13\) At $r = 1.69 \times 10^{-4}$ Cm\(^{-3}\) pulse\(^{-1}\), the error is equivalent to voltage drop of about 5 V, and the influence of the space charge is remarkable at low voltage setting for high charge density.

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Table 3. Comparison of ion collection efficiencies obtained using various analytical methods at a value of $r = 1.69 \times 10^{-4}$ Cm\(^{-3}\) pulse\(^{-1}\) (15 MeV electrons).

<table>
<thead>
<tr>
<th>$V_1$ (V)</th>
<th>$Q_1$ (nC)</th>
<th>$V_2$ (V)</th>
<th>$Q_2$ (nC)</th>
<th>$f_i$ (Eq. 1)</th>
<th>% error</th>
<th>$f_i$ (Eq. 9)</th>
<th>% error</th>
<th>$f_i$ (Eq. 4)</th>
<th>% error</th>
<th>$Q_{cyt}$ (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>40.03</td>
<td>250</td>
<td>38.68</td>
<td>0.9643</td>
<td>-0.34</td>
<td>0.9643</td>
<td>-0.34</td>
<td>0.9604</td>
<td>-0.74</td>
<td>0.9576</td>
</tr>
<tr>
<td>200</td>
<td>38.04</td>
<td>150</td>
<td>37.02</td>
<td>0.9638</td>
<td>-0.39</td>
<td>0.9638</td>
<td>-0.39</td>
<td>0.9604</td>
<td>-0.74</td>
<td>0.9576</td>
</tr>
<tr>
<td>100</td>
<td>35.17</td>
<td>50</td>
<td>30.35</td>
<td>0.9607</td>
<td>-0.71</td>
<td>0.9604</td>
<td>-0.74</td>
<td>0.9576</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>39.65</td>
<td>200</td>
<td>38.04</td>
<td>0.9566</td>
<td>-0.18</td>
<td>0.9565</td>
<td>-0.19</td>
<td>0.9512</td>
<td>-0.74</td>
<td>0.9583</td>
</tr>
<tr>
<td>300</td>
<td>39.15</td>
<td>150</td>
<td>37.02</td>
<td>0.9558</td>
<td>-0.26</td>
<td>0.9558</td>
<td>-0.26</td>
<td>0.9604</td>
<td>-0.74</td>
<td>0.9666</td>
</tr>
<tr>
<td>200</td>
<td>38.04</td>
<td>100</td>
<td>35.17</td>
<td>0.9401</td>
<td>-0.69</td>
<td>0.9400</td>
<td>-0.70</td>
<td>0.9400</td>
<td>-0.70</td>
<td>0.9666</td>
</tr>
<tr>
<td>100</td>
<td>35.17</td>
<td>50</td>
<td>30.35</td>
<td>0.9356</td>
<td>-1.16</td>
<td>0.9351</td>
<td>-1.21</td>
<td>0.9351</td>
<td>-1.21</td>
<td>0.9666</td>
</tr>
</tbody>
</table>

* Equation (4) is calculated from the effective electrode spacing, $d_{cyt, nom}$, obtained by Eq. (7)
The ion collection efficiency, $f(v)$, obtained as a function of $v$ from Eq. (4) is represented as a solid line in Fig. 3. Circles indicate the values of $f(v)$ on the solid line given by Eq. (4) using $d_{\text{cy}(\text{two})}$ in Table 4. Crosses indicate those given by Eq. (4) using $d_{\text{cy}(\text{nom})}$ in Table 1, 2, and 3, which are plotted as same abscissa values to Eq. (4) using $d_{\text{cy}(\text{two})}$. The dotted line shows a guide of eye for the crosses. Deviations of the results with Eq. (4) using $d_{\text{cy}(\text{nom})}$ compared to Eq. (4) using $d_{\text{cy}(\text{two})}$ are thought to be from a difference of the effective electrode spacing of the ionization chamber. They increase when the ion collection efficiency is less than 0.95. That is, Fig. 3 shows that errors of the dotted line compared to the solid line which resulted from small differences of the effective electrode spacing increase as the ion recombination loss increases.

6. CONCLUSIONS

The two-voltage technique is a useful method to correct the ion recombination loss when the influence of the space charge can be ignored. However, at high charge density, results with Boag's formula give a discrepancy between the experimental ion collection efficiencies estimated with the saturation charge by graphical extrapolation. This is because an unreliable value (nominal value) is used for the effective electrode spacing of the ionization chamber. To solve this problem,
we investigated the effect of the effective electrode spacing for real ionization chamber estimated with the two-voltage technique. The results with Boag's formula using the estimated effective electrode spacing agree much better with the experimental values even at high charge density.

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We are greatly indebted to Takao Takada, R.T., of the Kumamoto University Hospital, and Yoshiharu Higashida, Ph.D., of Kumamoto University College of Medical Science for their suggestions and discussions. We also wish to thank Toyo Medic Co., Ltd. for the generous loan of the RAMTEC 1000 Dose-Rate Meter.

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