Absolute Dose Rate Measurement of Very Soft and Weak X-rays by Means of a GM-counter

HAYASHI, Miyoko* and Satori HAYASHI*

(Received, 10 July 1964)

ABSTRACT

In order to determine the dose rate of X-rays having energies lower than 35 keV, a method that counting rate determined with a GM-counter was converted to dose rate was investigated. A radiation field of which intensity is near background can be measured by this method. Conversion coefficients from counting rate to dose rate were calculated as a function of photon energy for some GM-tubes available in Japan. The characteristics of the conversion coefficient were examined and the nature of GM-tube favorable for monitoring was discussed. By the proposed method a continuous X-ray field can be measured with a satisfactory accuracy and a precision of about 5%. The method can be applied to the determination of absorbed dose rate as well as exposure dose rate.

INTRODUCTION

An electron tube operated at a voltage over 5 keV can produce a X-ray field around itself. When an X-ray diffraction apparatus or a low voltage medical or industrial X-ray apparatus is used, the leaked or scattered X-ray dose rate level must be taken care of. For measuring such a soft X-ray almost all available survey meters can not be used because they are calibrated only in the energy region of over 30~40 keV. Furthermore, the measuring method must be considerably sensitive and be easy to be carried out for monitoring such X-rays.

In order to determine the leakage dose level from television receivers, Braestrup et al used an ionization chamber specially constructed. Oosterkamp et al calibrated a GM-counter by means of a standard free air chamber and a specially

* Osaka Public Health Institute, Morimachi, Osaka, Japan
constructed midway chamber for the same purpose\textsuperscript{3}). Callender \textit{et al} have converted counting rate to dose rate, measuring the X-ray spectrum by means of a side window proportional counter\textsuperscript{4}).

For measuring exposure dose rate the ionization chamber is most excellent in the principle. However, it can only afford a spatial or time average value of dose rate for a weak X-ray field owing to its low sensitivity. If such an apparatus as a vibrating reed electrometer is used in order to increase the sensitivity, highly careful handling become necessary. Calibration of a quantum counter by means of any standard ionization chambers is rather troublesome in procedure. Although the conversion method being used the proportional counter by Callender \textit{et al} is excellent, it is not considered suitable for field use in view of simple procedure.

In this work the authors investigated a method in which counting rate determined with a GM-counter was converted to dose rate for measuring a soft and weak X-ray field. Special attentions were paid to a reasonable coexistence of necessary precision and simplicity and to easiness of repetition of the by method other workers.

\section*{CONVERSION OF COUNTING RATE TO DOSE RATE IN THE CASE OF MONOCROMATIC X-RAYS}

When an X-ray is monochromatic, a counting rate determined is converted to dose rate by the following equation\textsuperscript{5,6)}:

\begin{equation}
R = 60 \frac{E}{\epsilon} \frac{\mu_{\text{air}}}{S} \frac{C}{0.0013} \frac{1}{10^3} \frac{1}{10^3} \frac{W}{e},
\end{equation}

where $E$ is the photon energy (keV), $S$ the effective window surface area of GM-tube (cm\textsuperscript{2}), $\epsilon$ the efficiency of GM-tube (ratio of the number of counted photons to the number of photons reached the GM-window), $\mu_{\text{air}}$ the energy mass absorption coefficient of air (cm\textsuperscript{2}/g), $W$ the energy necessary for the production of one ion pair in air, 34 eV, and $e$ the electronic charge, 4.8$\times$10\textsuperscript{-19} esu. $C$ is the counting rate, cpm, and $R$ is the exposure dose rate, mr/h. The numerator of the right side of the equation (1) is the real energy absorption (keV) per 1 g of air per hour at the point of interest and the denominator represents the absorbed energy (keV) per 1 g of air at the point where the exposure dose rate is 1 mr/h. In that case the beam is assumed to be homogeneous throughout the GM-window.

If it is assumed the photons are incident perpendicular to the window of an end-window GM-tube, the efficiency $\epsilon$ is represented by the next formula\textsuperscript{7)}:

\begin{equation}
\epsilon = \exp\left(-\mu_{\text{mica}} d\right) \cdot \exp\left(-\mu_{\text{argon}} \rho_{\text{argon}} x\right) \left\{1 - \exp\left(-\mu_{\text{argon}} \rho_{\text{argon}} y\right)\right\},
\end{equation}

where $x$ is the length of dead space behind the GM-window (cm), $y$ the effective length of GM-electrode (cm), $d$ the thickness of mica window (g/cm\textsuperscript{2}), $\rho$ the density (g/cm\textsuperscript{3}) and $\mu$ the mass absorption coefficient (cm\textsuperscript{2}) of the i material respectively. The suffix t represents that the $\mu$ is total absorption coefficient. The
efficiency $\epsilon$ corresponds to the product of the probability that the photon penetrates the mica window, the one that it penetrates the dead space behind the window and the one that it ionizes the atoms in argon layer of the effective electrode length. The effect of existence of quenching gas for the efficiency was neglected.

For one GM-tube $\epsilon$ and $S$ are constant. If the equation (1) is expressed as

$$ R = KC $$

$$ K = \frac{60 E}{\epsilon S \mu_{sir}^{2}} \left( \frac{1}{0.0013} \cdot \frac{1}{10^3} \cdot \frac{1}{10^3} \cdot \frac{W}{e} \right) - 1. \quad (3) $$

$K$ is a function of only energy. The values of $K$ were calculated concerning 4 GM-tubes of Japanese-make and shown in Fig. 1. The necessary data of these GM-tubes for calculation were tabulated in Table 1. The absorption coefficients after Grodstein$^b$ were mainly used, and the absorption coefficient for aluminum was substituted to that for mica.

Fig. 1. Conversion coefficients from counting rate (cpm) to dose rate (mr/h) for some GM-tubes those available in Japan.
Table 1. Some data for the GM-tubes

<table>
<thead>
<tr>
<th></th>
<th>TEN GM 131 A</th>
<th>TEN GM 134</th>
<th>ALOKA GM 2504</th>
<th>ALOKA GM 2504 LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window diameter</td>
<td>$\phi$ cm</td>
<td>2.5</td>
<td>1.6</td>
<td>2.45</td>
</tr>
<tr>
<td>Thickness of mica window</td>
<td>mg/cm²</td>
<td>2.8</td>
<td>2.5~3.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Length of dead space</td>
<td>x cm</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Length of electrode</td>
<td>y cm</td>
<td>2</td>
<td>10</td>
<td>3**</td>
</tr>
<tr>
<td>Pressure of argon</td>
<td>P mmHg</td>
<td>500</td>
<td>600</td>
<td>160</td>
</tr>
</tbody>
</table>

* uncertain  ** immediately measured

CONVERSION OF COUNTING RATE TO DOSE RATE IN THE CASE OF CONTINUOUS X-RAYS

In practical procedures of monitoring, fields of complex energy spectrum are usually treated. A representative K for an adopted GM-tube can not be settled because of the dependence of K on energy as shown in Fig. 1, unless the measurement with a rather large error is allowable.

In an ideal treatment the energy distribution of the X-ray should be determined by means of an NaI scintillator with a beryllium window or of its equivalents and

$$R_f = \int_{5\text{keV}}^{\text{max}} K(\text{E})C(\text{E})\,d\text{E}$$

should be calculated. The constituent having energy lower than 5 keV is not necessary to be considered because of its large absorption by air and others. This ideal procedure, however, is not practical for monitoring. To overcome this difficulty an effective energy is determined and the field under consideration is treated as a monochromatic field having that energy. In order to determine the effective energy an aluminum absorption curve is used.

The aluminum absorption curve has a curvature unless it is for a monochromatic X-ray. Let one, therefore, consider that the energy is determined on the basis of the first $1/2^n$ value layer. The larger the value n becomes, the larger the effective energy becomes gradually. In order to know how much value of n should be adopted, the following examination was done.

Being assumed various shapes of energy spectra, several absorption curves are drawn. From these imaginary curves the effective energy and then the effective K values are determined on the basis of the first $1/2^n$ value layer, where n is 1, 2, 3, .... Series of exposure dose rate values are obtained with these effective K values. These series were compared with the $R_f$ values obtained from the assumed spectra immediately by graphical integration. In spite of the variation of the most suitable n value between 2 and 7 according to the spectral shape, the dependence of dose rate value on n value was not very large. If 3 was adopted as the n value, the dose rate value obtained was not differ from the $R_f$ value beyond 5% except in the extreme case which would never appear
in practice.

A similar examination was done for 3 actual radiation fields near an electron tube "6 BK 4". In this case the following $R_2$ value had to be used as a substitute of the $R_f$ value. The absorption curve is assumed to be composite of exponential functions of finite number, then analyzed to 3 or 4 linear lines on a semilogarithmic paper. Thus,

$$R_2 = \sum_j K_j C_j$$

is calculated. Where $j$ represents each component. It had been ascertained that the $R_2$ value was in very good agreement with the $R_f$ value except in the extreme case at the step of examination of the imaginary absorption curves. This result was shown in Table 2. The adoption of 3 as the $n$ value is rational also in this case.

<p>| Table 2. Comparison of the dose rate values in mR/h obtained on the basis of 1/2$^a$ value layer with $R_2$ value |
|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>n</th>
<th>Field A</th>
<th>Field B</th>
<th>Field C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose rate values obtained on the basis of 1st 1/2$^a$ value layer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.56</td>
<td>0.59</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>2.59</td>
<td>0.59</td>
<td>0.34</td>
</tr>
<tr>
<td>3</td>
<td>2.62</td>
<td>0.60</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.61</td>
<td>0.63</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Effective energy from 1/8 value layer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 keV</td>
<td>11 keV</td>
<td>9 keV</td>
<td></td>
</tr>
</tbody>
</table>

In conclusion, the conversion coefficient $K$ should be determined for each radiation field from the effective energy which was obtained from the reduced half value layer as 1/3 of the first 1/8 value layer on the aluminum absorption curve. For convenience of practical use the values of $K$ for TEN GM 131 A were plotted as a function of half value layer in aluminum in Fig. 2.

EXPERIMENTS FOR ASCERTAINING THE VALIDITY OF THE METHOD

In order to ascertain the validity of the whole procedure mentioned above, the following 2 kinds of experiment were performed.

1. Measurement of a same X-ray field by the use of different kinds of GM-tube

An electron tube "6 BK 4" was used as the radiation source. Under some different conditions of the source, measurements were made by the use of 3 kinds of GM-tube. The results are shown in Table 3. The values obtained are in good agreement with each other in spite of the large difference of effective $K$ values.

2. Comparison with the value determined with an ionization chamber

In the measurement by the present method TEN GM 131 A was used. The value by the ionization chamber method was obtained with "Victoreen r-meter"
Fig. 2. K values for TEN 131 A as the function of half value layer in aluminum

Table 3. Comparison of the dose rate values in mr/h obtained by the use of various GM-tubes

<table>
<thead>
<tr>
<th>Distance from source (cm)</th>
<th>Al-absorber (mg/cm²)</th>
<th>TEN GM 131 A</th>
<th>ALOKA GM 2504</th>
<th>ALOKA GM 2504 LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>810</td>
<td>0.32</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>810</td>
<td>0.030</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>672</td>
<td>0.043</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>940</td>
<td>0.022</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>520</td>
<td>0.10</td>
<td></td>
<td>0.12</td>
</tr>
</tbody>
</table>

The radiation source is a "6 BK 4". The effective K values for these fields were 1,190 for TEN GM 131 A, 2,550 for ALOKA GM 2504 and 10,900 for ALOKA GM 2504 LB. The effective energy is 22 keV.

and "Victoreen chamber 576". The chamber has the volume of 170 ml and "Mylar" wall of 7 mg/cm² thick, and has been calibrated in NBS. As the radiation source "6 BK 4" was used. The difference of sensitivity between the GM-counter and the ionization chamber was compensated by the differences of the plate current of "6 BK 4" and of the time duration of the measurement. It had been ascertained that the leakage dose rate from "6 BK 4" was proportional to the plate current⁸). The leakage dose rate value from a "6 BK 4" operated at 25 kVp and 1 mA was 6.4 ± 0.6 mr/h in the present method and 6.1 ± 0.9 mr/h in the ionization chamber method at the point of 23 cm from the tube. The precision of the result were inferred as 10% in the former including that for the fluctuation of source conditions. In the ionization chamber method the error of 15% is reasonable by reason of the
corrections for the inhomogeneous radiation field and for the variation of source condition during the measuring period.

DISCUSSION

1. Characters of the K-energy curve

In the relatively high energy region (15 keV < ) the formula (2) representing the efficiency of a GM-tube is expressed as

\[ \varepsilon = \mu_{\text{argon}} \rho_{\text{argon}} \gamma = \text{const} \mu_{\text{argon}} P \gamma \]  

(4)

because of decreasing absorption coefficients. P is the pressure of argon sealed in the GM-tube. Thus the conversion coefficient

\[ K = \text{const} \frac{1}{P \gamma S} \frac{E \mu_{\text{Sr}}}{\mu_{\text{argon}}} \]  

(5)

Here \( \frac{1}{P \gamma S} \) is independent to energy and \( \frac{E \mu_{\text{Sr}}}{\mu_{\text{argon}}} \) depends on only energy. If the energy is constant, K is inversely proportional to P, y and S, and, therefore, the right half of the curves in Fig. 1 are almost parallel. An increase of K in the left half of the curves are related to the decrease of efficiency by the absorption of mica window and dead space.

When the measurement is carried out by the present method one must get a GM-tube for which reliable data can be obtained. Even if such a GM-tube can not be used, however, the K values of a certain GM-tube will be easy to calibrate with a GM-tube of which the K characteristic is well known, because the K-energy curves for arbitrary tubes show a similar form in each other beside slight differences in the energy region lower than 10 keV where photon absorption becomes more or less remarkable.

The energy dependence of K in the relatively high energy region can not be altered unless exchanging the sealed ionizing gas as recognized from the energy dependent part of the formula (5). Even if rare gases other than argon were to be used as the ionizing gas, however, particularly favorable results would not be gained in consideration of their absorption coefficients. In the case of TEN GM 131 A the largest value of K is about twice of the smallest value in the region of 5~30 keV. The energy dependency of the conversion coefficient of the argon GM-tube is acceptably good for the present method.

2. Sensitivity of the method and measurable extent of dose rate

The sensitivity of the measurement is a quantity proportional to 1/K. In case of the present examination the sensitivity of TEN GM 134 was largest and that of ALOKA GM 2504 LB smallest. If the value of K is 1,000×10^{-7} the counting rate of 100 cpm corresponds to the exposure dose rate of 0.01 mR/h. As to the sensitivity for our purpose the K value as small as this magnitude will be enough. It is considered that the end window GM-tube generally has a satisfactory sensitivity for
monitoring.

On the other hand, the upper limit of measurable counting rate by means of a GM-counter is about 20,000 cpm because of its relatively large resolving time. If $K$ is $1,000 \times 10^{-3}$, the counting rate corresponds to about 2 mR/h. When a more intense field must be measured, an aluminum absorber of appropriate thickness should be placed in front of the GM-tube. The multiplication factor can be determined by the measurement of a weaker field than 2 mR/h in which the energy distribution of photons is similar, or by the extrapolation of the aluminum absorption curve. In a practice of measurement, use of working curves for the adopted GM-tube which are made in consideration of the background count and counting loss are very convenient. An example is shown in Fig. 3.

Fig. 3. Working curves for obtaining the exposure dose rate value (mR/h) from the counting rate value (cpm) determined by use of TEN GM 131 A. The resolving time was assumed as 300 µsec and the background count as 30 cpm.
3. Effect of inclination of the GM-tube to the beam direction

The counting efficiency of the GM-tube for monitoring should not largely decrease when the GM-probe inclined to the beam direction. The correlation between the relative counting rate and the angle of inclination actually measured was presented in Fig. 4. In the case of TEN GM 134 the counting efficiency decrease to about 20% of the initial value for 15° inclination of the probe, although its sensitivity is high. Such a character is supposed to be unsuitable for monitoring when a field containing more or less scattered beams must be treated. The counting efficiency of TEN GM 131 A is kept in 70% even at 30° inclination of the probe. ALOKA GM 2504 LB was excellent at this viewpoint in spite of its low sensitivity. In conclusion, the ratio of the effective electrode length to the window diameter ($y/\phi$) should be less than unity.

Judging from the above results, one can conclude that a GM-tube for monitoring must have rather a large $P$ or $S$ but not $y$ to keep a necessary sensitivity (see the formula (5)) if it is technically possible. As a whole TEN GM 131 A was most suitable for monitoring in the examined 4 kinds of GM-tube.

4. Error accompanied with the method

The precision of the method will be influenced by the energy distribution of photons, existence of scattered beams in the measured field and the intensity level of dose rate etc., apart from the stability of the measuring apparatus. It was inferred as about 5% from the actual results of measurement and from the consideration of the precision of treating absorption curves, if the statistical error is not very large. The procedure of obtaining an absorption curve in order to keep the accuracy of the method is not considered so toilsome because only a rough measurement is enough to get the 1/8 value layer for treating a series of similar fields. If less precision of the measurement is allowable, the use of a counting rate meter instead of the counter, of course, is very convenient.
6. Measurement of absorbed dose rate

If the energy absorption coefficient for a certain material is known, an almost same method to that presented here can be applied to determine the absorbed dose rate to the material. The conversion coefficient (for i material) in this case

$$K_i = 60 \frac{E}{\epsilon \Sigma} \mu_i^i (100 \cdot \frac{1}{10^6} \cdot \frac{1}{1.6} \times 10^9)^{-1},$$

(6)

where the value $\frac{1}{1.6} \times 10^9$ represents keV per 1 erg. The unit of the obtained dose rate value is mrad/h.

CONCLUSION

For dose rate measurement of X-rays having energies between 5 and 35 keV the conversion method by means of a GM-counter is very convenient, especially in the case of low dose rate level. The energy characteristic of an argon GM-tube is considered to be acceptably good in that energy region. A GM-tube which has the larger window diameter than the electrode length is preferable to use. About 5% of precision of the measurement is obtained in a common case by adoption of the procedure presented for continuous X-rays.

ACKNOWLEDGEMENT

Authors are indebted to Prof. K. Otozai, Mr. S. Kume, Dr. S. Fukushima and other members of Radiochemistry Institute, Faculty of Science, Osaka University, for their valuable discussions and encouragements throughout the work. They are grateful to Mr. T. Kitao, Matsushita Electric Industrial Co. Ltd. for his kindness in the performance of the experiment. Thanks are also due to Kobe Kogyo Corp. and Nihon Musen Irigaku Institute Ltd. for their informations on the data of GM-tubes.

REFERENCES

New York.

