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Letter

Calibration of NaI (Tl) Scintillation Survey Meter Using Industrial X-ray Equipment

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We calculated an additional filter that can greatly attenuate the dose rate compared with the N-80 and N-100 X-ray calibration fields specified in ISO 4037-1 but with almost the same radiation quality. Using the Surface Dose Evaluation Code ver. 17 simulation software of Laboratory of Medical Radiology Technology and the Particle and Heavy Ion Transport System code of Japan Atomic Energy Agency, additional filters whose half-valent layers are almost the same as those of N-80 and N-100 were calculated. Next, we performed actual measurements using industrial X-ray equipment and confirmed that they were in agreement with the simulation results. Furthermore, we calibrated an NaI (Tl) scintillation survey meter and compared it with the calibration factors of a ^{137}Cs source. By setting additional filters of 2.5 mm Al + 1.0 mm Cu + 1.0 mm Ta at 80 kV and 2.5 mm Al + 2.0 mm Cu + 2.0 mm Pb at 100 kV, radiation quality similar to those of N-80 and N-100 was achieved. It was also found that the dose rate was significantly attenuated. The calibration factors of the survey meter were almost the same as the energy characteristics. We found that NaI (Tl) scintillation survey meters can be calibrated using industrial X-ray equipment.

1. Introduction

The main targets of external radiation measurements are X-rays, γ-rays, and neutrons. External radiation measurement is required by several Japanese laws and regulations. In addition, it is common to use different types of survey meters to measure external radiation in accordance with the type, energy, and intensity of the radiation.(1)

There are several types of survey meters (ionization chamber type, GM tube type, semiconductor type, etc.), among which scintillation survey meters, which are the most sensitive

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to photons, are considered useful for measuring trace amounts of radiation leaking into controlled areas. However, their energy dependence in the low-energy region is stronger than those of other survey meters. Therefore, although ^{137}Cs sources (662 keV) are used as reference sources for calibration and energy-compensated survey meters have been developed in recent years, their energy characteristics differ from those of the X-ray diagnostic region, and they must be calibrated using the energy of the X-ray diagnostic region to be used for X-ray leakage measurement.(2) Radioactive isotopes with energy in the diagnostic range include ^{241}Am sources (59 keV); however, in Japan, ^{241}Am sources are mainly used for industrial gauges (such as thickness gauges) and are rarely supplied to medical institutions.(3) The ISO 4037-1 standard describes how to calibrate instruments using a continuous X-ray reference field in addition to a γ-ray reference field.(4–6) Although there are several types of continuous X-ray reference fields, the use of the narrow-spectrum series (N-series)(7) is recommended worldwide for calibrating survey meters.(4) The N-series has various radiation qualities with tube voltages ranging from 10 to 300 kV, and it is considered appropriate to use N-80 or N-100 as the standard for the radiation quality of the calibration field of survey meters.(7) Since NaI (Tl) scintillation survey meters are limited to low dose rates, it is necessary to adjust the tube current and source-to-detector distance when using industrial X-ray equipment to calibrate them with continuous X-ray standard fields. However, the number of facilities with industrial X-ray systems in Japan is minimal compared with that of medical facilities, and it is difficult to calibrate all survey meters. Although previous studies have reported calibration by adding lead plates to the γ-ray source to attenuate the dose rate,(8) this approach has not yet been examined in continuous X-ray reference fields. Therefore, we believe that by identifying a combination of additional filters capable of significantly attenuating the dose rate while satisfying the reference values of the N-series specified in ISO 4037-1, it will be possible to confirm and calibrate survey meters that have already been calibrated at each medical facility using the medical X-ray equipment installed there in the future (hereinafter referred to as "calibration").

In this study, we calculated the combination of additional filters that would provide almost the same radiation quality as those of N-80 and N-100, which are considered the reference radiation qualities for calibration fields in the X-ray diagnostic region, and we investigated whether the dose rate can be significantly attenuated and whether the calibration of NaI (Tl) scintillation survey meters is possible using industrial X-ray equipment.

2. Materials and Methods

2.1 Investigation of optimal additive filter by simulation

Simulations were performed using Surface Dose Evaluation Code ver. 17 software of Laboratory of Medical Radiology Technology(9) (SDEC-V17), whose radiation quality is almost identical to the reference radiation qualities of N-80 and N-100, to obtain a combination of additional filters that can reduce the dose rate. Regarding the combination of additional filters, assuming the calibration of medical X-ray equipment in the future, 2.5 mm Al, which is specified as the minimum thickness for the total filtration of X-ray tube equipment,(10,11) was used as the fixed filter, and other filters were added. After obtaining the optimal combination of additional filters with SDEC-V17, the Particle and Heavy Ion Transport System code of Japan Atomic Energy Agency[12] (PHITS) was used to obtain the first half-valent layer (HVL_1; mm Cu) and the second half-valent layer (HVL_2; mm Cu).

2.2 Evaluation of continuous X-ray standard field by actual measurement

Figure 1 shows the experimental system constructed with reference to ISO 4037-1[4] and JIS Z 4511[13] to investigate whether the simulation results calculated as described in Sect. 2.1 match the measured values. The combination of additional filters calculated in Sect. 2.1 (purity of each material ≥ 99.9%) was inserted in the line bundle. Using this condition as a reference, a copper (Cu) plate (purity ≥ 99.9%) was added gradually, and an attenuation curve was drawn from the measured values to obtain the first and second half-valent layers (mm Cu). The irradiation conditions for the industrial X-ray equipment (ISOVOLT Titan E, GE Sensing & Inspection Technologies) were tube voltages of 80 and 100 kV, a tube current of 10 mA, and an irradiation time of 30 s. The average of five measurements was taken for each measured value to minimize measurement error. Since the measured values in this study were very small, they may have been affected by background values or leakage currents in the measurement system. Therefore, the following corrections were made when calculating the net measurement value. (1) The background was measured before the thickness of each Cu plate was measured to obtain the background value b for the irradiation time. (2) Considering the effect of the opening and closing times of the shutter of the industrial X-ray equipment, the shutter was opened 2 s after the electrometer (EMF520R, EMF Japan) measurement started, and the electrometer measurement was completed 2 s after the shutter closed. (3) The net measured value N was calculated using Eq (1), where I is the integrated value during the measurement time and a is the measured value for 2 s before opening the shutter.

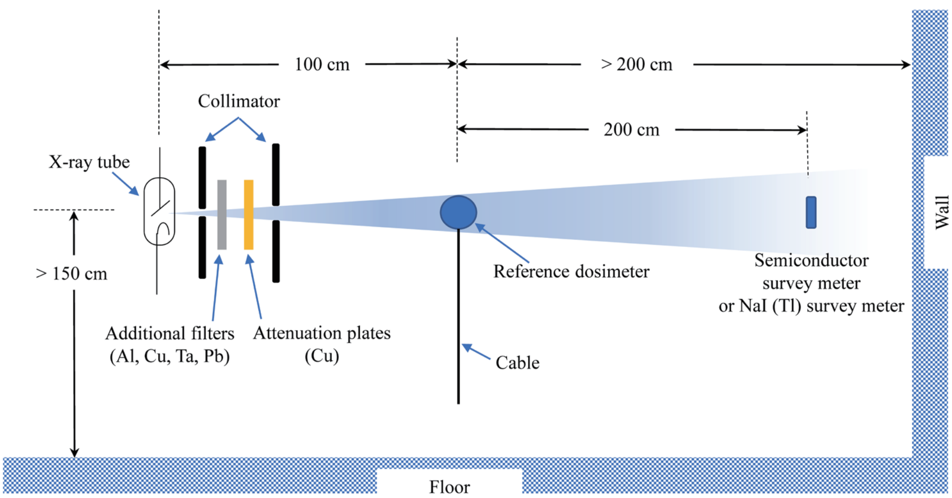

Fig. 1. (Color online) Side view of experimental setup.

$$N = I - 2a - b \tag{1}$$

The first and second half-valent layers were respectively calculated using Eqs. (2) and (3).[14] Using these values for the first and second half-valent layers, the homogeneity coefficient was obtained as $h = HVL_1/HVL_2$. In addition, the linear attenuation coefficient μ (cm^{-1}) and the mass attenuation coefficient μ/ρ (cm^2-g^{-1}) were obtained from the first half-valent layer, the mass attenuation coefficient of Cu at 40 to 150 keV was taken from the National Institute of Standards and Technology,[15] an approximate curve and approximate equation were generated, and the mass attenuation coefficient was substituted into the approximate equation to obtain the effective energy E_{eff} (keV). Here, the density of Cu, which is 8.94 g-cm^{-3} according to ISO 4037-1,[4] was used. The quality index ($QI = E_{eff}/E_{max}$) was then obtained from the derived effective energy, and these values are compared with the results of the PHITS simulation and the reference values of N-80 and N-100. The dose rate was measured for tube currents of 0.1, 0.5, 1, 5, and 10 mA and compared with the reference dose rates of N-80 and N-100. Since the tube current was self-calibrated in the device, the indicated value was used. The measurable range of the NaI (Tl) scintillation survey meter (TCS-172B, Nippon RayTech; calibrated using a ^{137}Cs source in January 2021) was limited to <30 μSv/h,[16] which is a low dose. Therefore, it was considered that the dose rates of N-80 and N-100 could not be measured; thus, they were measured using a semiconductor survey meter (RaySafe452, Fluke Biomedical; calibrated using a ^{137}Cs radiation source in October 2021) installed at a distance of 3 m from the X-ray tube focal point.

$$HVL_1 = \frac{t_1 \ln\left(2I_2 / I_0\right) - t_2 \ln\left(2I_1 / I_0\right)}{\ln\left(\mathrm{I}_1 / \mathrm{I}_2\right)} \tag{2}$$

$$HVL_2 = \frac{t_3 \ln\left(4I_4 / I_0\right) - t_4 \ln\left(4I_3 / I_0\right)}{\ln\left(I_3 / I_4\right)} - HVL_1 \tag{3}$$

I_0: Measured value when irradiated without a Cu plate.
I_1 (I_3): Measured value when slightly larger than $I_0/2$ ($I_0/4$).
I_2 (I_4): Measured value when slightly less than $I_0/2$($I_0/4$).
t_1 (t_3): Thickness of Cu plate when I_1(I_3) is measured.
t_2 (t_4): Thickness of Cu plate when I_2(I_4) is measured.

2.3 Calibration of NaI (Tl) scintillation survey meter

To verify that the NaI (Tl) scintillation survey meter can be calibrated in an industrial X-ray system, we replaced the reference dosimeter [1 L chamber: TN32002 (PTW)] in Fig. 1 with a TCS-172B scintillation survey meter. Since its measurable range is <30 μSv/h,[16] we adjusted the distance and tube current referring to the results of the measurements in Sect. 2.2 so that it was measurable. The time constant of TCS-172B was set to 30 s, and the irradiation duration was set to 120 s, considering the time constant. The calibration factors (CFs) obtained from the measurement value of TCS-172B and the measurement value of the 1 L chamber were calculated using Eq. (4) and compared with the CFs at the ^{137}Cs source. Additionally, since the measured value of the 1 L chamber was converted from μGy/30 s to μSv/h, which is the unit of the measured value of TCS-172B.(6,13) The relative expanded uncertainty of the CF for each was also calculated.(17,18)

$$CF = \frac{N_A \bullet 120 \bullet h^*_K}{N_B \bullet \left(\frac{C_A}{C_B}\right)} \times \left(\frac{D_A}{D_B}\right)^2 \tag{4}$$

N_A: Measured value for 1 L chamber
N_B: Measured value for TCS-172B
h^*_K: Air kerma-dose equivalent conversion coefficient
C_A: Tube current for 1 L chamber measurement
C_B: Tube current for TCS-172B measurement
D_A: Source-to-detector distance when measuring in 1 L chamber
D_B: Source-to-detector distance when measuring in TCS-172B

3. Results

3.1 Evaluation of optimal additive filter by simulation

Table 1 shows the simulation results obtained using SDEC-V17. By setting the combination of additional filters of 2.5 mm Al + 2.0 mm Ta at 80 kV and 2.5 mm Al + 3.0 mm Pb at 100 kV, it was found that the radiation quality was almost the same as the reference values for N-80 and N-100 (error within 2.5%). In addition, PHITS simulations were performed to determine the half-valent layers in the Cu plate with the above combination of additional filters. The results for the first and second semi-valent layers were close to the reference values for the N-80 and N-100 half-valent layers(4) (error within 6.3%) (Table 2).

3.2 Evaluation of continuous X-ray standard field by actual measurement

Measurements were made with the combination of additional filters determined in Sect. 3.1. At 80 kV, a plateau was reached before the measured value was attenuated by 50%. At 100 kV, the first half-valent layer differed from the reference value of N-100 by more than 10%. Table 3 shows the results of another simulation performed using SDEC-V17. When 2.5 mm Al + 1.0 mm Cu + 1.0 mm Ta at 80 kV and 2.5 mm Al + 2.0 mm Cu + 2.0 mm Pb at 100 kV were set as the combination of additional filters, although the rate of attenuation of the dose rate was lower than that of the combination of additional filters described in Sect. 3.1, since the radiation quality was close to the reference radiation qualities of N-80 and N-100, we changed the combination of additional filters and measured it again. Tables 4 and 5 show the measured values and the

Table 1
Simulation results obtained using SDEC-V17.

Tube voltage (kV)	Combination of additional filters	HVL_1 (mm Al)	E_{eff} (keV)
80	4.0 mm Al + 2.0 mm Cu (N-80)	9.94	63.32
	2.5 mm Al + 2.0 mm Ta	10.18	64.57
100	4.0 mm Al + 5.0 mm Cu (N-100)	13.05	82.36
	2.5 mm Al + 3.0 mm Pb	13.07	82.52

Table 2
Simulation results using PHITS.

Tube voltage (kV)	Combination of additional filters	HVL_1 (mm Cu)	HVL_2 (mm Cu)
80	4.0 mm Al + 2.0 mm Cu (N-80)	0.58	0.62
	2.5 mm Al + 2.0 mm Ta	0.62	0.62
100	4.0 mm Al + 5.0 mm Cu (N-100)	1.11	1.17
	2.5 mm Al + 3.0 mm Pb	1.15	1.16

Table 3
Results of additional simulation.

Tube voltage (kV)	Combination of additional filters	HVL_1 (mm Al)	E_{eff} (keV)
80	4.0 mm Al + 2.0 mm Cu (N-80)	9.94	63.32
	2.5 mm Al + 1.0 mm Cu + 1.0 mm Ta	9.89	63.07
100	4.0 mm Al + 5.0 mm Cu (N-100)	13.05	82.36
	2.5 mm Al + 2.0 mm Cu + 2.0 mm Pb	12.95	81.60

Table 4
Measured and N-80 values.

	This work	N-80	Error (%)
HVL_1 (mm Cu)	0.58	0.58	−0.52
HVL_2 (mm Cu)	0.59	0.62	−5.16
H	0.98	0.75 to 1.00	—
E_{eff} (keV)	64.7	65.0	—
QI	0.81	0.83	—

Table 5
Measured and N-100 values.

	This work	N-100	Error (%)
HVL_1 (mm Cu)	1.16	1.11	4.32
HVL_2 (mm Cu)	1.25	1.17	6.41
H	0.93	0.75 to 1.00	—
E_{eff} (keV)	85.3	83.0	—
QI	0.85	0.83	—

reference values of N-80 and N-100, respectively. The differences between the first and second half-valent layers were −0.52 and −5.16% at 80 kV and 4.32 and 6.41% at 100 kV. Figures 2 and 3 show the dose rates obtained by changing the tube current for the above combination of additional filters and the reference dose rates for N-80 and N-100, respectively. The combinations of additional filters proposed in this study resulted in a dose rate lower than 100 μSv/h even at a tube current of 10 mA.

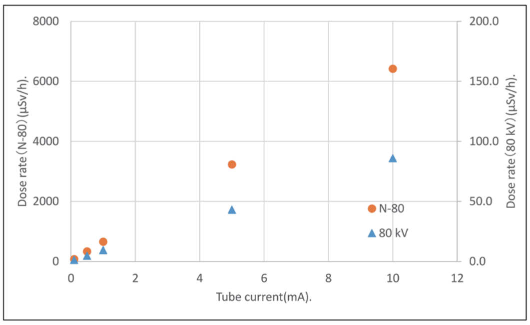

Fig. 2. (Color online) Dose rates at 80 kV.

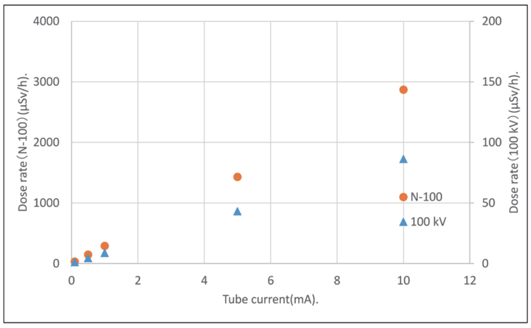

Fig. 3. (Color online) Dose rates at 100 kV.

3.3 Evaluation of calibration of NaI (Tl) scintillation survey meters

On the basis of the results in Sect. 3.2, the irradiation conditions for TCS-172B measurements were set to a source-to-detector distance of 200 cm and a tube current of 1 mA. Table 6 shows the survey meter calibration results and calibration uncertainties. The CFs were 1.31 at 80 kV and 1.10 at 100 kV. The CF when calibrated with the ^{137}Cs source was 1.10. The CFs at 80 and 100 kV were normalized using this value, and a graph of the normalized CFs and the energy characteristics of TCS-172B is shown in Fig. 4. It is clear that the calibration results of this study are in close agreement with the energy characteristics of TCS-172B.(16)

4. Discussion

Simulation results show that adding 2 mm Ta to 2.5 mm Al at 80 kV and adding 3 mm Pb to 2.5 mm Al at 100 kV produce first and second half-valent layers that are almost identical to those of N-80 and N-100, respectively. This is thought to be because Ta and Pb have energy absorption edges at 67.8 and 88.4 keV, respectively, and the energy absorption edges make the radiation quality harder.(15) However, exponential attenuation of the integrated dose was not observed in the actual measurement, the half-valent layer could not be measured, and the first half-valent layer showed a large deviation between the simulation and reference values. The N-80 and N-100 filters specified in ISO 4037-1 are composed of a combination of Al and Cu plates.(4) However, 2 mm Ta and 3 mm Pb, which were considered a useful combination of additional filters in the simulation, have a much stronger attenuation effect than Al and Cu plates in the N-80 and N-100 energy ranges. Therefore, even if a Cu plate is added for half-valent layer measurement, a thickness difference of about 0.1 mm would have almost no effect on attenuation. In addition, since the aim of this study was to calibrate an NaI (Tl) scintillation survey meter, the measured values were very small. Therefore, although the net measured values were calculated by applying a correction for the leakage current to the actual measured values, it is possible that the resolution limit of the electrometer and reference dosimeters was reached.(19,20) The additional filter combinations (2.5 mm Al + 1 mm Cu + 1 mm Ta at 80 kV and 2.5 mm Al + 2 mm Cu + 2 mm Pb at 100 kV) obtained via the additional simulation exceeded ± 5% in the second half-valent layer

Table 6
Survey meter calibration.

X-ray series (kV)	CF	Relative expanded uncertainty (%)
80	1.31	8.66
100	1.10	8.67

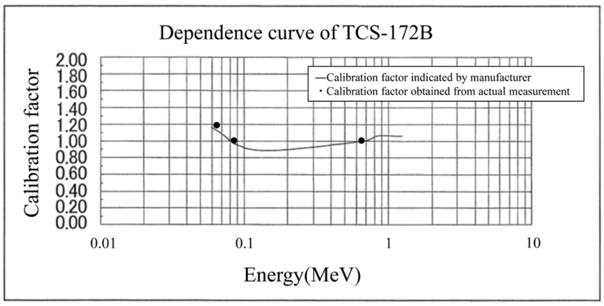

Fig. 4. Comparison of calibration factors and energy characteristics of TCS-172B. (This figure is used with permission from the manufacturer.)

compared with the N-80 and N-100 reference values. However, since this difference is small and the other results were in agreement with the reference values of N-80 and N-100, it is considered that radiation quality almost equivalent to those of N-80 and N-100 can be reproduced.

The CFs of TCS-172B in this study were almost identical to its energy characteristics. This is thought to be because almost the same radiation quality as those of N-80 and N-100 was reproduced even with different combinations of additional filters, because a correction was made to obtain the net measured value of the reference dosimeter, and because a sufficient irradiation duration was set considering the time constant of the survey meter, resulting in stable measurement values. The experimental system in this study can be reproduced in facilities where industrial X-ray equipment is installed, and the dose rate can be significantly attenuated compared with those of N-80 and N-100 specified in ISO 4037-1. Therefore, the combination of the additional filters proposed in this study is considered useful for calibrating NaI (Tl) scintillation survey meters, whose measurable range is limited to low doses at energies in the diagnostic range.

In this study, Ta plates were used at 80 kV and Pb plates were used at 100 kV to attenuate the dose rate; however, there is a possibility that a different combination of additional filters can reproduce radiation quality similar to those of N-80 and N-100. The limitation of the TCS-172B scintillation survey meter used in this study is that it is an energy-compensated survey meter; thus, we were unable to examine the possibility of using a survey meter without energy compensation. In addition, it is necessary to consider the time constant when calibrating the survey meter using a medical X-ray device with a short irradiation duration. The indicated value of the survey meter is $1–\exp(–t/T)$[1] times the final indicated value X, where t is the measurement time and T is the time constant. Hence, if the measured value at time t is x, then x =

$X(1-\exp(-t/T))$. Therefore, $X = x/(1-\exp(-t/T))$ is used to obtain the final indicated value from the measured value at time t. Further studies are required to confirm that the final indicated value after correction for the time constant is consistent with the dose rate in this study and that the survey meter can be calibrated.

5. Conclusions

In this study, we calculated a combination of additional filters for calibrating a NaI (Tl) scintillation survey meter using industrial X-ray equipment. As a result, by setting additional filters of 2.5 mm Al + 1.0 mm Cu + 1.0 mm Ta at 80 kV and 2.5 mm Al + 2.0 mm Cu + 2.0 mm Pb at 100 kV, almost the same radiation quality as those of N-80 and N-100 was obtained. Additionally, it was found that the dose rate can be greatly attenuated to the measurable range of the NaI (Tl) scintillation survey meter. Furthermore, it was noted that the radiation quality can be used to calibrate NaI (Tl) scintillation survey meters. A ^{137}Cs source with an energy of 662 keV is used as a reference source for the calibration of NaI (Tl) scintillation survey meters. It is necessary to calibrate these survey meters using the energy of the X-ray diagnostic region to measure leaked X-rays. We proposed a method of calibrating NaI (Tl) scintillation survey meters using the energy in the X-ray diagnostic region.

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