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Functional Confirmation Using a Medical X-Ray System of a Semiconductor Survey Meter

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Abstract

In recent years, semiconductor survey meters have been developed and are in increasing demand worldwide. This study determined if it is possible to use the X-ray system installed in each medical facility to calculate the time constant of a semiconductor survey meter and confirm the meter's function. An additional filter was attached to the medical X-ray system to satisfy the standards of N-60 to N-120, more copper plates were added as needed, and the first and second half-value layers were calculated to enable comparisons of the facility's X-ray system quality with the N-60 to N-120 quality values. Next, we used a medical X-ray system to measure the leakage dose and calculate the time constant of the survey meter. The functionality of the meter was then checked and compared with the energy characteristics of the meter. The experimental results showed that it was possible to use a medical X-ray system to reproduce the N-60 to N-120 radiation quality values and to calculate the time constant from the measured results, assuming actual leakage dosimetry for that radiation quality. We also found that the calibration factor was equivalent to that of the energy characteristics of the survey meter.

Keywords

Semiconductor Survey Meter, Functional Confirmation, Medical X-Ray System, Calibration Factor, Time Constant

1. Introduction

Semiconductor survey meters are more sensitive, fast-responding, compact, and lightweight than ionization-chamber survey meters and are also less affected by atmospheric pressure and humidity; therefore, semiconductor survey meters are widely used in the nuclear, medical, and industrial fields [1] [2] [3]. Given their high sensitivity, fast response, small size, and light weight, these survey meters are considered useful for measuring weak leakage radiation, but they are highly energy- and temperature-dependent [4] [5] [6] [7]. Therefore, it is difficult to make a correct assessment of leakage radiation unless the survey meter is traceable and has been calibrated and valued in the radiation reference field described below.

JIS Z 4511^{-2018} (revised 2018) is a Japanese Industrial Standard based on ISO 4037-1^{-1996}, ISO 4037-2^{-1997}, ISO 4037-3^{-1999}, and ISO 4037-4^{-2004}, with the technical content modified according to the conditions of use in Japan. The standard stipulates the setting of the air-kerma standard field, the method of calibrating the dose-equivalent (rate) measuring device used for the radiation protection field and personal monitoring, and the test method of the response to photon energy and the radiation incident angle [8] [9] [10] [11] [12]. The standard also applies to the air-absorbed dose (rate), air kerma (rate), and irradiation dose (rate) measuring instruments.

Calibration of survey meters used in radiation therapy in the medical field, nuclear medicine facilities, and measurement of leaky X-rays in the diagnostic area is performed with 662 keV γ-rays emitted from ^{137}Cs sources. A functional verification then must be performed, which is a simple calibration to determine if the performance of the survey meter calibrated according to the frequency of use and usage conditions is sustained after calibration and if the calibration factor can continue to be used. The functional check should confirm that the indicated value from a low-level γ-ray source emitting low radioactivity is normal, and a ^{137}Cs source or ^{60}Co source should be used for the functional check. However, facilities that have ^{137}Cs and ^{60}Co sources are limited to those that have blood irradiation equipment and radiotherapy equipment. Therefore, it is difficult to confirm functionality in facilities that do not have radiation sources. The ISO standard describes not only γ-ray reference fields but also continuous X-ray reference fields [9] [10] [11] [12]. There are several types of continuous X-ray reference fields, and the narrow-spectrum series (N-series) is suitable for evaluating the energy characteristics of detectors [9]. The leakage X-rays in the diagnostic area are 50 keV to 100 keV, so the radiation quality is equivalent to N-60 to N-120 for the N-series. Therefore, if the N-series can be reproduced with the medical X-ray equipment installed in medical facilities, it will be possible to confirm the survey meter function even in facilities that do not have ^{137}Cs sources or ^{60}Co sources. In addition, when measuring X-ray leakage in relation to the functional confirmation of survey meters, an essential condition for accurate measurement is that the time constant is working properly. Since the measurement of leaky X-rays is a short-time measurement and some semiconductor survey meters do not allow the time constant to be set manually, we believe that accurate measurement of leaky X-rays will be possible if the N-series radiation quality can be used to calculate the time constant of the survey meter. However, medical X-ray systems are not designed for the purpose of detector calibration and cannot be exposed to X-rays for a long period of time.

The study aim was to determine if it is possible to use a medical X-ray system to reproduce the radiation qualities of the N-60 to N-120 series and to calculate the time constant and confirm the functionality of a semiconductor survey meter.

2. Methods

2.1. Equipment Used

The medical X-ray system used in this study was a UD150B-40 (Shimadzu corporation, total filtration 3.7 mm Al, checked in August 2022), and the semiconductor survey meter was a RaySafe452 (Fluke Biomedical). An EMF520R electrometer (EMF Japan) (checked in June 2020) was used with a 1-L chamber for the TN32002 (PTW, calibrated in June 2020) reference dosimeter. Additional filters used were copper (Cu), aluminum (Al), and tin (Sn) plates. The purity of each material is ≥99.9%, and each plate measures 10 cm × 10 cm and has a thickness of 0.1 mm to 2 mm. A ^{137}Cs source with a radiation quality of N-100 was used to calibrate the RaySafe452 in October 2021, and this calibration ensures the accuracy of the specifications defined in the product.

2.2. Evaluation of Continuous X-Ray Standard Fields

To determine if it is possible to provide N-60 to N-120 radiation quality with a medical X-ray system, we set up an experimental system (**Figure 1**), referring to JIS Z 4511^{-2018} [8]. The total filtration specific to the medical X-ray equipment used was 3.7 mm Al, and the combination of additional filters from N-60 to N-120 were 4 mm Al + 0.6 mm Cu (N-60), 4 mm Al + 2 mm Cu (N-80), 4 mm Al + 5 mm Cu (N-100), and 4 mm Al + 5 mm Cu + 1 mm Sn (N-120). Therefore, Al, Cu, and Sn plates were attached to the radiation window of medical X-ray system to meet the respective standards. Then, the Cu plates were sequentially added,

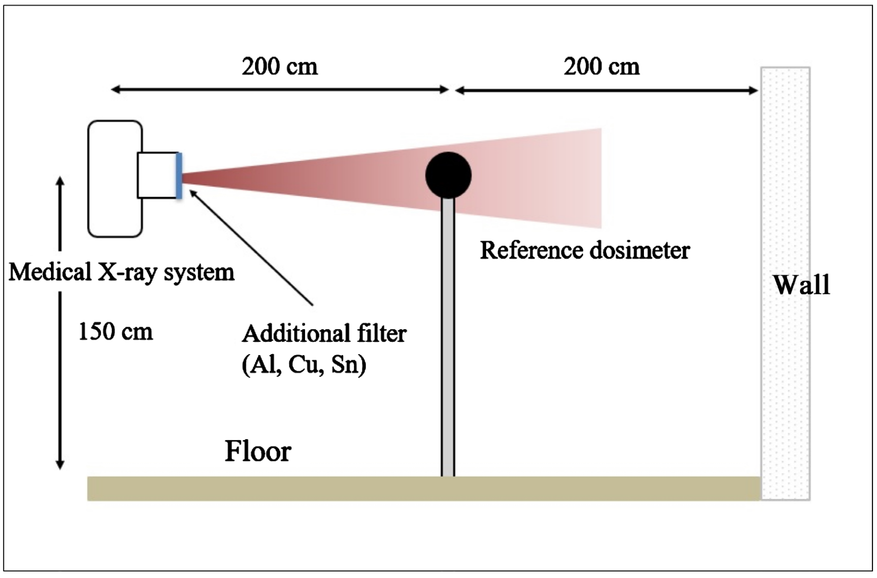

Figure 1. Side view of the experimental setup.

and attenuation curves were created from the actual measurement values to obtain the first half-value layer (HVL_1) and the second half-value layer (HVL_2) (mm Cu). Furthermore, the homogeneity coefficient (h), effective energy (E_{eff}), and quality index (QI) are calculated from the values of HVL_1 and HVL_2. The X-ray irradiation conditions were a tube current of 100 mA, irradiation time of 2.0 s, and a large focus, and the measured values were the average of five measurements to minimize the measurement error. Equation (1) was used to calculate HVL_1, and Equation (2) was used for HVL_2 [13]. These values were compared with the reference values of N-60 to N-120. Note that evaluation items for continuous X-ray standard fields include average energy and resolution. It is desirable to confirm by spectrum measurement that the average energy is ±3% and the resolution is ±10% from the reference values for each radiation quality level. However, since spectrum measurement requires a spectrometer, it is difficult to perform spectrum measurement in facilities that do not have a spectrometer. Therefore, in this study, we evaluated radiation quality using the first and second half-value layers, which can be calculated by use of a simple method. If it matches the reference value of N-60 to N-120 radiation quality within ±5%, the radiation quality is assumed to have been reproduced sufficiently. In addition, the dose rate (mSv/h) at this time is calculated from the measured value of the 1-L chamber (nC) according to Equation (3).

$$HVL_1 = \frac{d_1 \ln\left(2I_2/I_0\right) - d_2 \ln\left(2I_1/I_0\right)}{\ln\left(I_1/I_2\right)} \tag{1}$$

$$HVL_2 = \frac{d_3 \ln\left(4I_4/I_0\right) - d_4 \ln\left(4I_3/I_0\right)}{\ln\left(I_3/I_4\right)} - HVL_1 \tag{2}$$

I_0: Measured when irradiated without a copper plate;

I_1 (I_3): measurements slightly greater than $I_0/2$ ($I_0/4$);

I_2 (I_4): measurements slightly smaller than $I_0/2$ ($I_0/4$);

d_1 (d_3): thickness of the copper plate when I_1 (I_3) was measured;

d_2 (d_4): thickness of the copper plate when I_2 (I_4) was measured.

$$DR_A = M_A \times C_A \times h_K \times 1800 \tag{3}$$

DR_A: Dose rate [mSv/h].

M_A: Measured value for 1-L chamber [nC/2s].

C_A: Calibration factor for 1-L chamber [2.55 × 104 [Gy/C] for N-60, 2.51 × 104 [Gy/C] for N-80, 2.50 × 104 [Gy/C] for N-100, 2.49 × 104 [Gy/C] for N-120].

h_K: Air kerma-dose equivalent conversion coefficient [1.59 [Sv/Gy] for N-60, 1.73 [Sv/Gy] for N-80, 1.71 [Sv/Gy] for N-100, 1.64 [Sv/Gy] for N-120].

2.3. Evaluation of Continuous X-Ray Standard Fields

A measurement time of 3 to 4 times the time constant has been recommended for accurate measurement with a survey meter. However, X-ray imaging in the diagnostic field uses short exposures. Therefore, it is necessary to measure leaked

X-rays in a very short time, and it is not possible to secure a measurement time that is 3 to 4 times the time constant.

Therefore, we devised a method of calculating the time constant by calculation. The indicated value of a survey meter is $1 - \exp^{-t/T}$ [14] with respect to the final indicated value, where the measurement time is t and the time constant is T. Therefore, if the measured value at time t is x and the final indicated value is X, then Equation (4) can be expressed as shown below.

$$x = X\left(1-\exp\left(-\frac{t}{T}\right)\right) \quad (4)$$

By transforming Equation (4), time constant T can be expressed as Equation (5).

$$T = -\frac{t}{\ln\left(1-\frac{x}{X}\right)} \quad (5)$$

where x is the measured value of each irradiation time and X is the largest value of the measured values.

In addition, to use the time constant obtained from Equation (5) to verify that the calculated value matches the measured value, we established a system as shown in Figure 2, which assumes that an actual leakage X-ray measurement is

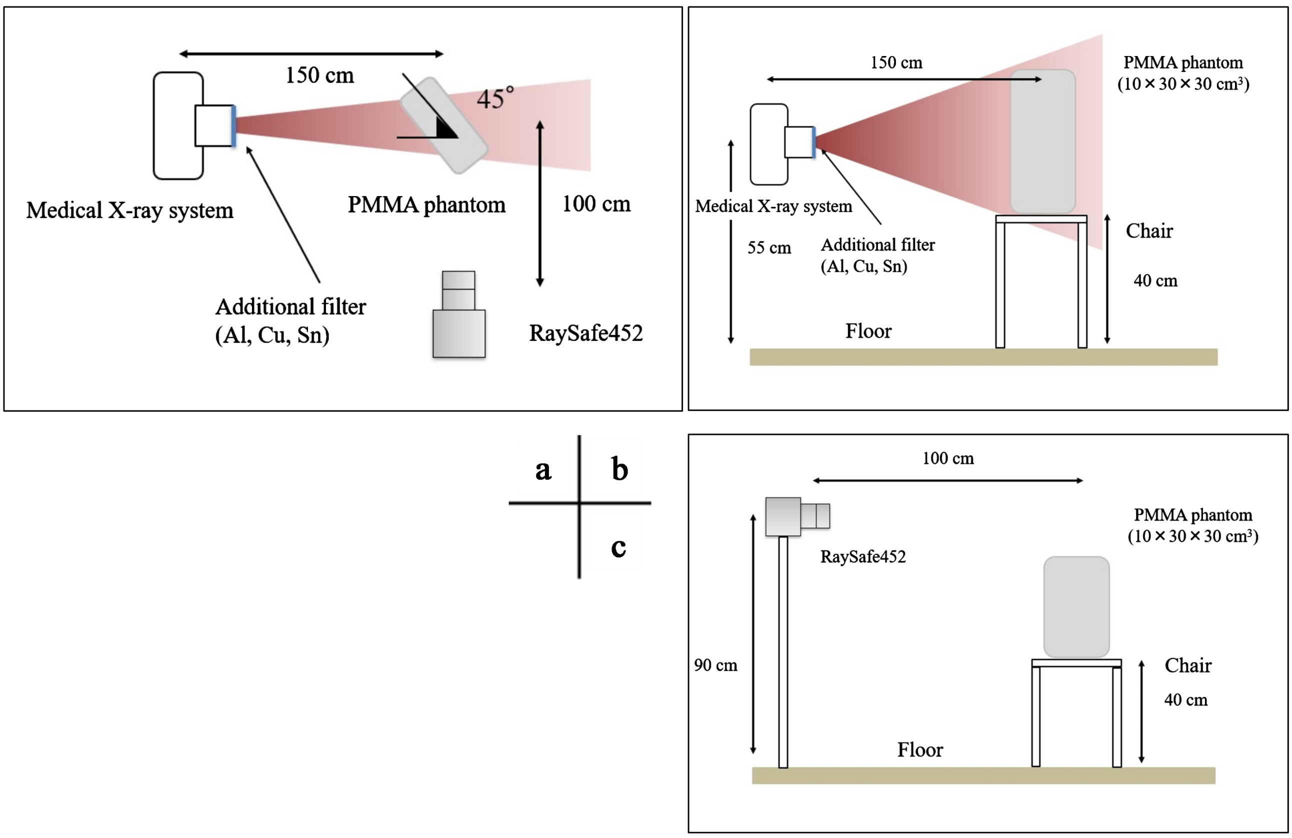

Figure 2. Geometry assuming leaked dosimetry. (a) Top view of the experimental setup; (b) Positional relationship between the medical X-ray system and PMMA viewed from the side; (c) Positional relationship between the RaySafe452 and PMMA viewed from the side. PMMA: polymethyl methacrylate.

made. Using this system, measured values were obtained by changing the irradiation time from N-60 to N-120 to 0.20, 0.28, 0.36, 0.50, 0.63, 0.80, 1.0, 1.2, 1.6, 2.0, and 2.5 s. The time constant was calculated according to Equation (5). Although the time constant can be obtained by extracting only one measurement point from each irradiation time, the indicated value of the survey meter is $1 - \exp^{-t/T}$ [14] with respect to the final indicated value. Therefore, since the calculated results are expected to vary greatly depending on the measurement point, the average value of the Equation (5) calculated results for each irradiation time was used as the time constant. Then, assuming that the calculated time constant is T in Equation (4) and the largest value of the measured values is X, the values at each irradiation time were calculated and compared with the measured values. Measurements were taken 10 times, and the average value was calculated after excluding outliers using the interquartile range. For irradiation durations ≥ 1.6, the measured value was stable, so the average of five measurements was used, taking into account the load on the X-ray tube.

2.4. Functional Confirmation of Semiconductor Survey Meter

To determine if it was possible to use a medical X-ray system to confirm the functionality of a semiconductor survey meter, a survey meter was installed in the same position as that in the experimental system shown in **Figure 1**. There are several methods for checking the functionality of the survey meter, but in this study, the substitution method was used to reduce the calibration uncertainty [15]. The same irradiation conditions as in 2.2 were used, and the reported value was the average of five measurements to reduce the measurement error. From these results and the results of 2.2, the calibration factor (CF) was calculated according to Equation (6) and compared with the energy characteristics of the RaySafe452. The relative expanded uncertainty of the functional verification for each reference value for N-60 to N-120 was calculated [16] [17].

$$CF = \frac{DR_A}{DR_B \cdot \frac{C_A}{C_B}} \times \left(\frac{D_A}{D_B}\right)^2 \tag{6}$$

DR_A: Measured value for 1-L chamber;

DR_B: Measured value for the RaySafe452;

C_A: Tube current for 1-L chamber measurement;

C_B: Tube current for RaySafe452 measurement;

D_A: Source-to-detector distance when measuring in the 1-L chamber;

D_B: Source-to-detector distance when measuring in the RaySafe452.

3. Results

3.1. Evaluation of Continuous X-Ray Standard Fields

Table 1 shows the comparison between the measured values in this study and the reference values for N-60 to N-120. The results show that HVL_1 and HVL_2 in

Table 1. Comparison of measurement value and N-60 to N-120. (a) N-60; (b) N-80; (c) N-100; (d) N-120.

(a)

	This work	ISO4037-1	Error (%)
HVL_1 (mm Cu)	0.58	0.58	−0.34
HVL_2 (mm Cu)	0.62	0.62	−0.16
h	0.93	0.75 - 1.0	-
E_{eff} (keV)	65	65*	-
QI	0.81	-	-

(b)

	This work	ISO4037-1	Error (%)
HVL_1 (mm Cu)	0.24	0.24	−0.42
HVL_2 (mm Cu)	0.27	0.26	1.92
h	0.90	0.75 - 1.0	-
E_{eff} (keV)	46	48*	-
QI	0.76	-	-

(c)

	This work	ISO4037-1	Error (%)
HVL_1 (mm Cu)	1.73	1.71	−1.35
HVL_2 (mm Cu)	1.79	1.77	0.85
h	0.97	0.75 - 1.0	-
E_{eff} (keV)	100	100*	-
QI	0.83	-	-

(d)

	This work	ISO4037-1	Error (%)
HVL_1 (mm Cu)	1.11	1.11	0.45
HVL_2 (mm Cu)	1.17	1.17	0.09
h	0.95	0.75 - 1.0	-
E_{eff} (keV)	84	83*	-
QI	0.84	-	-

HVL_1, first half-value layer; HVL_2, second half-value layer. *; Mean energy (keV).

the measured values of this study slightly differed from the reference values for N-60 to N-120, but the difference was ≤1.92% and within ±5%; therefore, they can be regarded as the same radiation quality [8]. These results make it clear that a medical X-ray system can be used to reproduce the radiation quality values of N-60 to N-120. In addition, the calculated dose rates from N-60 to N-120 were 196.04 (mSv/h) for N-60, 113.69 (mSv/h) for N-80, 47.63 (mSv/h) for N-100, and 48.37 (mSv/h) for N-120.

3.2. Evaluation of the Calculation of Time Constants for Semiconductor Survey Meters

Figure 3 shows a graph comparing the measured values for each N-60 to N-120 quality and the calculated values using the time constant calculated from Equation (5), with the horizontal axis representing the X-ray irradiation time in seconds and the vertical axis representing the dose rate (mSv/h). The time constants were 0.73 s for N-60, 0.82 s for N-80, 0.75 s for N-100, and 0.73 s for N-120 (ranging from 0.7 - 0.8 seconds), which were consistent with the RaySafe452 specification [18], and the calculated values obtained from the calculated time constants were also almost consistent with the measured values. Therefore, it is clear that a medical X-ray system can be used to calculate the time constants of the RaySafe452.

3.3. Evaluation of Semiconductor Survey Meter Function Confirmation

Table 2 shows the survey meter calibration results and calibration uncertainties calculated according to Equation (6). The calibration factors were 1.03 for N-60,

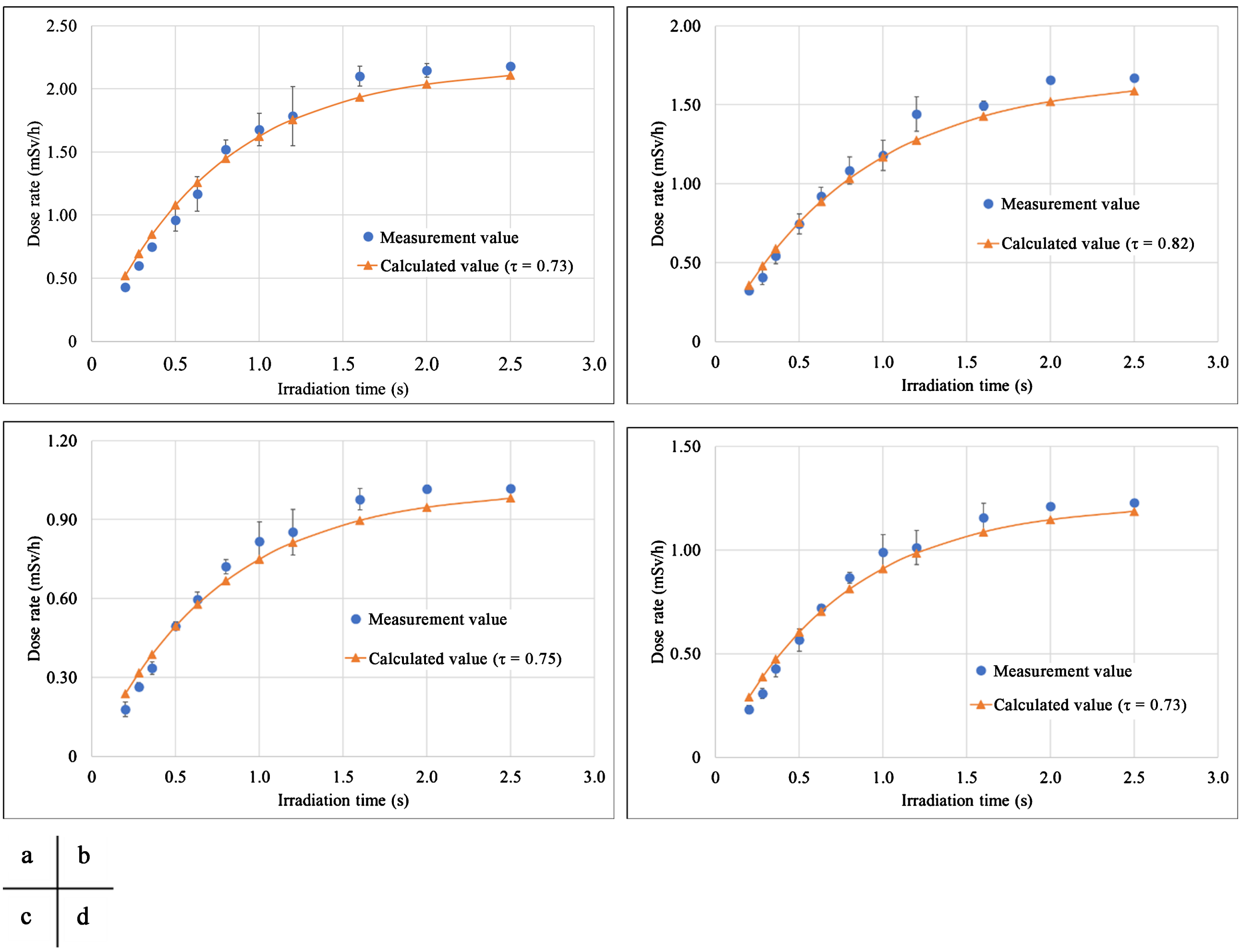

Figure 3. Comparison of measurement value and calculated value. (a) N-60; (b) N-80; (c) N-100; (d) N-120.

Table 2. Survey meter functional confirmation.

X-ray series	Calibration factor	Relative expanded uncertainty (%)
N-60	1.03	9.23
N-80	1.04	9.23
N-100	1.04	9.23
N-120	1.01	9.25

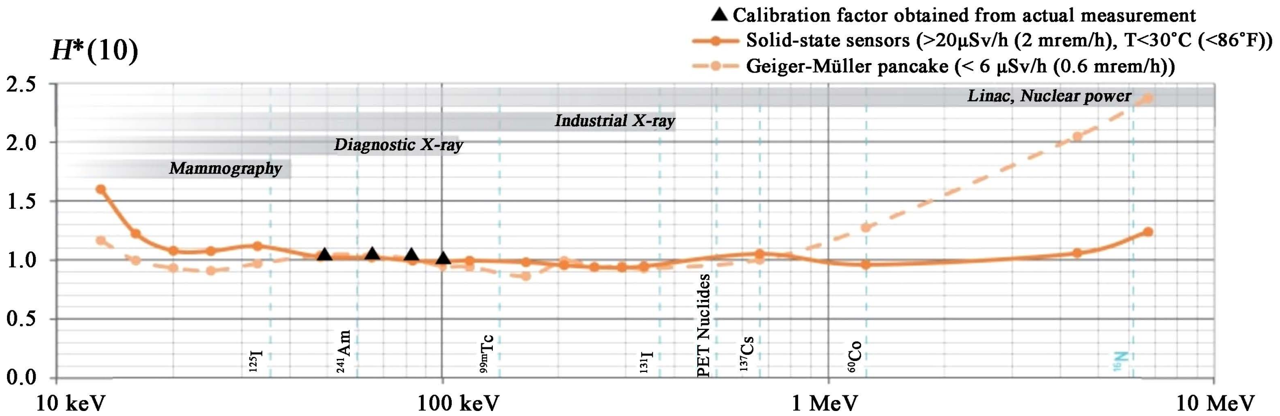

Figure 4. Relationship between calibration factors and energy characteristics of the RaySafe452. (This figure is used with permission from the manufacturer.)

1.04 for N-80, 1.03 for N-100, and 1.01 for N-120. In addition, Figure 4 shows the relationship with the energy characteristics of the RaySafe452, where the horizontal axis is the average energy $\overline{E}$ (keV) and the vertical axis is the calibration factor. It is clear that the results of the functional verification in this study are in close agreement with the energy characteristics of the RaySafe452 [18].

4. Discussion

When the radiation qualities of N-60 to N-120 were reproduced by use of a medical X-ray system, the values of the first and second half-value layers were almost consistent with the reference values in ISO 4037-1 [9]. This result could be because the current inverter-type X-ray systems have a rise and fall time of <1 ms, which greatly improves the short-time characteristics [19], so that the output is stable even with short irradiation durations and meets the conditions specified as a continuous X-ray standard field. The reason for the slight error is that medical X-ray system uses tungsten as a target to irradiate X-rays [19]. Therefore, the characteristic X-ray component of tungsten had a slight influence on the measured values, and it is thought that HVL_1 and HVL_2 were also affected. In addition, when comparing the dose rates of the N-60 to N-120 radiation qualities, we found that the dose rate tended to decrease as the tube voltage increased. However, only the N-120 radiation quality showed a slightly higher value than the N-100 radiation quality. This result is thought to be because the additional filter used for N-120 has an additional Sn plate added to the additional filter for

N-100, but the X-ray penetration power has increased due to the increased tube voltage. Furthermore, since the energy absorption edge of Sn is 29.3 keV, it is thought that this is because the attenuation effect was weak in the energy region of N-120 [20]. In this study, experiments were performed by attaching Al, Cu, and Sn plates, which are additional filters, directly to the movable X-ray aperture. Once the experimental system was set up, the radiation quality could be reproduced by adjusting the tube voltage and switching to the corresponding additive filter.

In the method of determining the time constants of the survey meter by calculation, some variation in the measured values was observed, especially in short-time imaging. This variation is thought to be because the RaySafe452 has a time constant for the stabilization of the measured values according to the dose rate, and the dose rate in the experimental system of this study did not allow sufficient time for stabilization [18]. It is thought to be necessary to consider this point when calculating the time constant with the RaySafe452. Especially, when the irradiation time is short, the number of measurements must be increased, as in this study, and the interquartile range should be used to remove the influence of outliers to obtain the measured value. Additionally, dose rate measurements may require additional time to stabilize at a low measurement value after a high measurement value due to scintillator afterglow within the solid-state sensor [18]. Therefore, it is considered necessary to set the measurement interval to ensure the accuracy of time constant calculation, especially when performing a measurement with a long irradiation time and then a short measurement. As mentioned at the beginning of this discussion, it is possible to reproduce the radiation quality of N-60 to N-120 with a medical X-ray system. Since the method of calculating the time constant is a reproducible system, if there is a scatterer, such as made from PMMA (polymethyl methacrylate), in addition to the filter, it can be implemented in every medical facility. The method proposed in this study is considered useful for improving the accuracy of leakage dose measurements during short-time radiography.

The calibration factors when using a medical X-ray system had approximately the same values as the energy characteristics of the RaySafe452. Since RaySafe452 is in a state where the accuracy of the specifications defined by the product is guaranteed through calibration, this result proves that this state is maintained. This is because, in addition to reproducing the radiation quality of N-60 to N-120, the semiconductor survey meter has high sensitivity and fast response, so even with a short irradiation time, the RaySafe452 measurement value reaches a plateau. This is thought to be due to stable values being measured. This characteristic indicates that the time constant of the RaySafe452 is ≤2 s [16]; however, it was <1 s for the dose rates irradiated by the experimental system in this study, which is consistent with the calculated results. Since the irradiation conditions in this study can be reproduced by the medical X-ray systems installed in other medical facilities, functional confirmation using medical X-ray systems is considered possible. However, the JIS Z 4511^{-2018} stipulates that X-ray equipment that generates a continuous X-ray standard field must have a tube voltage ripple of ≤10%. Therefore, it is necessary to confirm that the conditions are met [8]. Furthermore, since medical X-ray systems are not designed to irradiate X-rays for long periods of time, it is necessary to consider the load on the X-ray tube, such as leaving intervals between irradiations, especially at 100 kV and 120 kV.

There were several study limitations that should be considered with evaluating our results. 1) The RaySafe452 used in this study has only a dose-rate mode for measurement; so we were not able to study the totalization mode. 2) The method of determining the time constant by calculation requires an X-ray irradiation duration of approximately 2 seconds, so the method developed in this study cannot be used for X-ray systems with a maximum irradiation duration of <2 seconds. 3) The minimum tube current that could be set with the medical X-ray system used in this study when the irradiation time was 2 seconds was 100 mA. Therefore, the dose rates for N-60 to N-120 reproduced using these irradiation conditions ranged from 45 to 190 mSv/h, and studies outside the above dose range have not been possible. If it is possible to find a combination of additional filters that can significantly attenuate the dose rate while satisfying the reference values of the N-series, it would be possible to confirm the functionality of survey meters whose measurable range is limited to low dose rates. These matters require additional study in the future.

5. Conclusion

In this study, we determined if it was possible to use a medical X-ray system to reproduce the N-60 to N-120 (the N-series) radiation quality levels, which are specified in the ISO standard and suitable for evaluation of detector energy characteristics. We found that by installing additional filters to meet the standards of N-60 to N-120, it was possible to reproduce the same radiation qualities of N-60 to N-120. In addition, when we used the N-60 to N-120 radiation quality levels to calculate the time constant of a semiconductor survey meter, we were able to calculate a time constant that matched the manufacturer's specifications. As a result of confirming the functionality of the semiconductor survey meter, we found that it was possible to confirm the functionality since it almost matched the energy characteristics. The experimental system used in this research can be reproduced in the X-ray radiography rooms of other typical medical facilities, so a reference dosimeter with traceability, additional filters, and medical X-ray equipment that has been adjusted can be used to confirm the semiconductor survey meter.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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