Derivation of total filtration thickness for diagnostic x-ray source assembly

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Abstract

The method defined by the IEC 60522 for determining the inherent filtration of an x-ray source device is applicable only for a limited range of tube voltage. Because the users cannot legally remove the x-ray movable diaphragm of the x-ray source device, total filtration, which is the sum of the additional filtration diaphragm movable for specific filtration and x-ray, cannot be measured. We develop a method for simply obtaining the total filtration for different tube voltage values.

Total filtration can be estimated from a ratio R' of the air kerma K'_{x+T}, which is measured with an Al plate with thickness T, and K'_x measured without an Al plate. The conditions of the target material of the x-ray source device are then entered into the Report 78 Spectrum Processor to calculate the air kerma K_x and K_{x+T} for Al thicknesses x and $(x + T)$, respectively, to obtain R. The minimum value of x, which is the difference between the R and R', is the total filtration of the x-ray source device.

The total filtration calculated using the industrial x-ray source device was within $\pm1\%$ in the 40–120 kV range. This method can calculate the total filtration using air kerma measurements with and without the Al plate. Therefore, the load on the x-ray tube can be reduced, and preparation of multiple Al plates is not necessary. Furthermore, for the 40–120 kV tube voltage range, the user can easily measure the total filtration.

Keywords: total filtration thickness, diagnostic x-ray source assembly, x-ray spectrum, tube voltage

(Some figures may appear in colour only in the online journal)

1. Introduction

Diagnostic x-ray source devices comprise an x-ray tube device and an x-ray movable diaphragm enclosing the x-ray tube device in an x-ray tube housing. X-ray flux is emitted to the outside of the transmitted x-ray source unit mirror and the cross plate (acrylic) in the movable diaphragm that insulates oil, the x-ray circulating in the glass wall, and the x-ray tube housing of the x-ray tube. A filter composed of aluminum or copper is also present, which reduces the radiation exposure by removing the radiation in the soft x-ray region of the spectrum. The total filtration is defined as the sum of the additional filtration by a filter, for the purpose of moving the diaphragm and the radiation quality hardening inherent filtration, and the x-ray by the x-ray tube apparatus itself, for the diagnostic x-ray source device. The total filtering is specified in terms of aluminum (Al) equivalents and must be equal to or greater than the 2.5 mm Al, according to IEC 60601-1-3 (IEC 2008).

The method for determining the inherent filtration of the x-ray source device is defined by the IEC60522 as the total dose equivalent filtration or ripple percentage of 10% or less. The first half value layer (HVL_{1st}) method is the most commonly used method for determining the total filtration (IEC 1999). This value is considered as acceptable if it is within 100%–130% of the nominal value. Nagel has evaluated the inherent filtration due to HVL_{1st} and obtained an error of $\pm30\%$ for the characteristic generated x-ray of the tungsten (W) tube voltage that is desirable to avoid (Nagel 1988). Meghzifene *et al* studied a method for determining the thickness of a specific filter using the fitting of the attenuation curves measured with the diagnostic x-ray source device for the thickness of the intrinsic filtering in the calculation (Meghzifene *et al* 2006). The calculation of the x-ray spectrum considered the tube voltage, tube voltage pulsation rate, target angle, and an additional filter; an inherent filtration match in the range of -7.6%–6.4% was reported. This method for obtaining the inherent filtration thickness is better than the methods of Nagel, suggesting that it is more accurate to compare the measured values with the method determining the calculated x-ray spectra.

The inherent filtration obtained by the above method is applicable for only a limited range of tube voltage. However, the x-ray flux emitted from the x-ray source device is transmitted through a material other than Al. Therefore, the total filtering represented by an Al equivalent will vary depending on the tube voltage changes. Furthermore, the user cannot measure the additional filtration diaphragm movable for specific filtration and x-ray, because the user cannot legally remove the x-ray movable diaphragm of the x-ray source device. Thus, the calculation of the incident surface dose calculation software and x-ray spectra are within the range of values specified in the Annexure and equipment of the x-ray source device as the total filtration (Cranley *et al* 1997, Kato *et al* 2009). This study has devised a method for conveniently obtaining the total filtration for different values of the tube voltage.

2. Theory and materials

2.1. Theory

For any of the tube voltage E_{max} of the x-ray tube having a target material and the target angle, air kerma K_x is expressed by equation (1) in the focus–detector distance D (mm) that has passed through the Al equivalent total filtration thickness x (mm Al).

$$K_x = \int_0^{E_{max}} \left[\left(\frac{d\phi(E)}{dE} \right) (1 - \exp(-\mu(E) \cdot x)) \right] \cdot E \cdot \left[\frac{\mu_{en}(E)}{\rho} \right]_{air} dE, \quad (1)$$

where $\mu(E)$ is the linear attenuation coefficient for the energy E, $\mu_{en}(E)/\rho$ is the mass energy absorption coefficient, and $\phi(E)$ represents the photon influence. Then, near of the x-ray focal point to insert a known Al plate T (mm), air kerma K_{x+T} is represented by the formula (2) in D that has passed through the Al equivalent total filtration thickness $x + T$ (mm Al). And we determined (1) and (2) the ratio of the formula R (3).

$$K_{x+T} = \int_0^{E_{max}} \left[\left(\frac{d\phi(E)}{dE} \right) (1 - \exp(-\mu(E) \cdot x + T)) \right] \cdot E \cdot \left[\frac{\mu_{en}(E)}{\rho} \right]_{air} dE, \qquad (2)$$

$$R = \frac{K_x}{K_{x+T}}. \qquad (3)$$

This ratio R determines each of the calculations and measurements. The Al equivalent total filtration thickness x is calculated by finding the x difference between the determined by calculation and R' obtained by the actual measurement and R is minimized by trial and error.

The calculated value of air kerma used a Report 78 Spectrum Processor (Birch and Marshall 1979, Cranley *et al* 1997). For this software, the tube voltage (30–150 kV), tube voltage ripple rate (0%–30%), the target material (W, Mo, and Rh), target angle (6°–22°), and 32 kinds of transparent material with the smallest unit of thickness (0.01 mm) can be arbitrarily selected. However, air kerma is calculated as the direct line of air kerma (μGy/mAs) in a vacuum of distance D of 750 mm. Therefore, to assemble the same measurement arrangement it needs to be assigned as an air transmission material of 750 mm. Thus, the measurement is the same measurement arrangement by measuring D as 750 mm.

The measurement procedure is shown in figure 1. First, air kerma K_x of the Al equivalent total filtration thickness x is measured at a distance of x-ray source device D (=750 mm). Next, the air kerma K'_{x+T} is measured at the time the known Al plate T was added to the Al equivalent total filtration thickness $x+T$. And it calculated the ratio R' (figure 1(a)). The conditions of the target material of the x-ray source device are then entered into Report 78 Spectrum Processor in order to calculate the air kerma K_x and K_{x+T} for Al thicknesses x and $x+T$, respectively, to obtain the R (figure 1(b)). Here, the minimum x, which is the difference between the R and R', is the Al equivalent total filtration of the x-ray source device.

2.2. Materials

Diagnostic x-ray equipment and industrial x-ray equipment were used as the x-ray apparatus. The x-ray tube apparatus of the industrial x-ray device ISOVOLT 160 M2 (GE Co., USA) was used with a W target, the target angle of 20°, and a radiation port with filtration by a 1 mm thickness of beryllium (Be) window only. In the high-voltage device ISOVOLT Titan E (GE Co., USA), the tube current pulsation rate and tube voltage pulsation rate are smaller than ±1%; the high voltage cable length is 5 m and is comparable to the constant voltage device. For the x-ray tube apparatus of the diagnostic x-ray equipment DRX-422HD-S (Toshiba Co., Japan), the target was W and the target angle was 12°. A TF-6TL-6 (Toshiba Co., Japan) was used as the x-ray variable diaphragm. DRX-422HD-S is 1.1 mm Al/75 kV, TF-6TL-6 is 1.2 mm Al/70 kV, with an additional 0.2 mm Al filter, and the total filtration is displayed as 2.5 mm Al. KXO-80G (Toshiba Co., Japan) was used as the high-voltage device.

Al plate (Goodfellow Cambridge Ltd, UK) at 99.999% purity was used for nominal thicknesses of 0.5, 1.0, 2.0, and 3.0 mm. The thickness of the Al plate was measured at five points
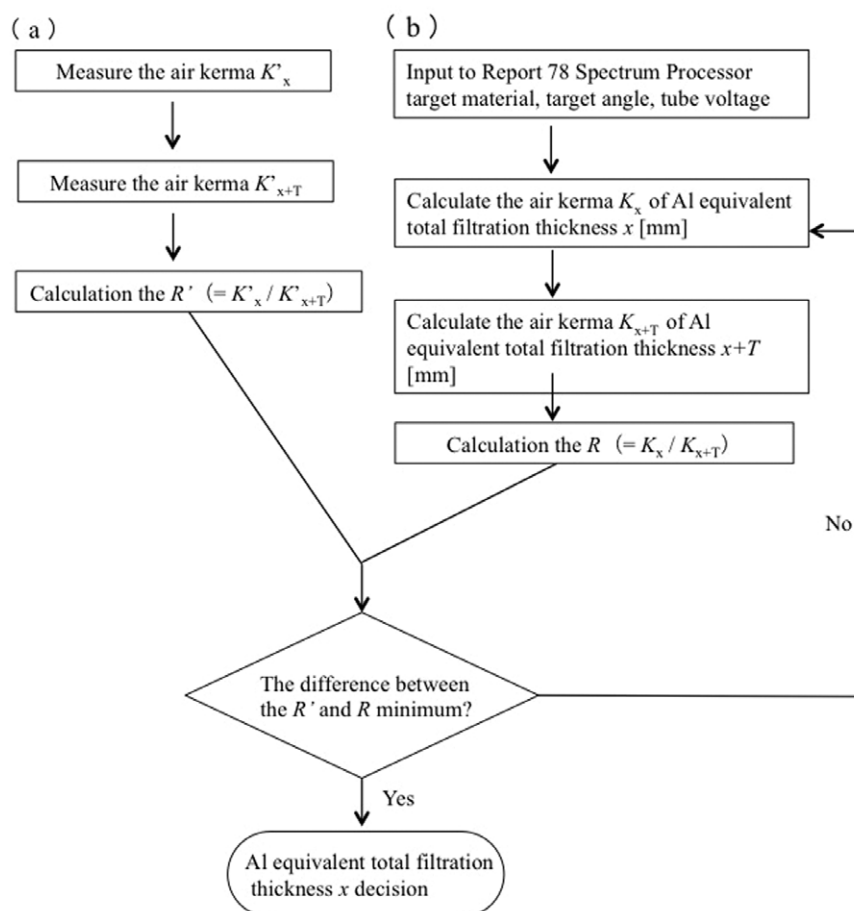
(a)

```
┌─────────────────────────────┐
│ Measure the air kerma K'ₓ   │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ Measure the air kerma K'ₓ₊ₜ │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ Calculation the R' (= K'ₓ / K'ₓ₊ₜ) │
└─────────────────────────────┘
```

(b)

```
┌──────────────────────────────────────┐
│ Input to Report 78 Spectrum Processor │
│ target material, target angle, tube voltage │
└──────────────────────────────────────┘
                    │
                    ▼
┌──────────────────────────────────────┐
│ Calculate the air kerma Kₓ of Al equivalent │
│ total filtration thickness x [mm]     │
└──────────────────────────────────────┘
                    │
                    ▼
┌──────────────────────────────────────┐
│ Calculate the air kerma Kₓ₊ₜ of Al    │
│ equivalent total filtration thickness x+T │
│ [mm]                                  │
└──────────────────────────────────────┘
                    │
                    ▼
┌──────────────────────────────────────┐
│ Calculation the R  (= Kₓ / Kₓ₊ₜ)      │
└──────────────────────────────────────┘
```

The difference between the R' and R minimum?

No

Yes

Al equivalent total filtration thickness x decision

Figure 1. Flow chart of the total filtration thickness measurement. (a) is measured, (b) side the course of calculation. The difference between R' and R is minimum or judgment. If large, redo the calculation (No side). For the minimum case, the calculated x is an Al equivalent total filtration thickness (Yes side).

with a micrometer (Mitutoyo Co., Japan) to obtain a precision of ±0.01 mm. Furthermore, we measured the mass (g) of each filter using an electronic balance, measured the length of the four sides and the diagonal with calipers, and calculated the area (cm²) from equation. Henceforth, the thickness of the Al plate was calculated using the following equation:

$$x = \frac{M}{s \cdot \rho}, \tag{4}$$

where ρ is the density and is equal to 2.699 (g cm⁻³). The thickness of the Al plate was evaluated using equation (4) and it was confirmed that there are no differences with the directly measured values. The measured thickness values for the Al plate are shown in table 1.

For the measurement of air kerma, we used the Model 9015 (Radcal Co., USA) dosimeter and the 10 × 5 − 6 (Radcal Co., USA) detector. This combination of the dosimeter and detector shows a ±2% variation in the energy characteristics in the 30–45 keV effective energy range, and calibration constants are obtained from the Japan Quality Assurance Organization (JQA).

Table 1. Nominal thicknesses and the measured thicknesses of the Al plate.

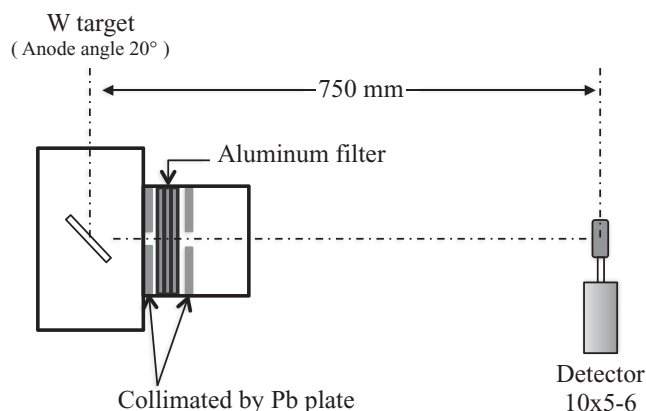| Nominal thickness (mm Al)	Measured thickness (mm Al)
0.5	0.51
1.0	1.08
2.0	1.95
3.0	3.02

Figure 2. Setup diagram for air kerma ratio measurement of the industrial x-ray equipment. X-ray tube has inherent filtration of only 1.0 mm thick Be, the total filtration x by an optionally added filter. The side scatter from the Al filter reduced by sandwiching the Al filter at the 5 mm thick Pb collimator. The focus-detector distance was around 750 mm and no influence of backscattering was observed.

3. Methods

3.1. Verification of report 78 spectrum processor

We used the industrial x-ray source device to validate the Report 78 Spectrum Processor. The $10 \times 5 - 6$ detector was placed 750 mm away from the target focus in order to measure each air kerma K'_x for the nominal Al plate values of 0.5, 1.0, 2.0, 3.0 mm, and an unknown filtration thickness x. The air kerma K'_{x+T} was then measured by inserting the Al plate of known thickness T to determine the respective ratios R'. The measurement arrangement is shown in figure 2. The sample was placed around the $10 \times 5 - 6$ to avoid the effect of backscatter. The beam was collimated by 5 mm thickness of Pb to eliminate the influence of side scatter from the inserted Al plate. The following irradiation conditions were used: tube voltage of 40–120 kV (10 kV step), tube current of 5 mA, and an irradiation time of 10 s. Then, we found the ratio R based on the measured conditions by calculating air kerma K_x, and the K_{x+T} by the Report 78 Spectrum Processor. It was examined whether the difference between the R' and R is equal to the total filtration thickness of the smallest x that is actually the inserted Al equivalent.

The industrial x-ray source device is the total filtration of the Be window only. Diagnostic x-ray source devices comprise an x-ray tube device and an x-ray movable diaphragm enclosing the x-ray tube device in an x-ray tube housing. X-ray flux is emitted to the outside of the transmitted x-ray source unit mirror and the acrylic plate in the movable diaphragm that insulates oil, the x-ray circulating in the glass wall, and the x-ray tube housing of the x-ray
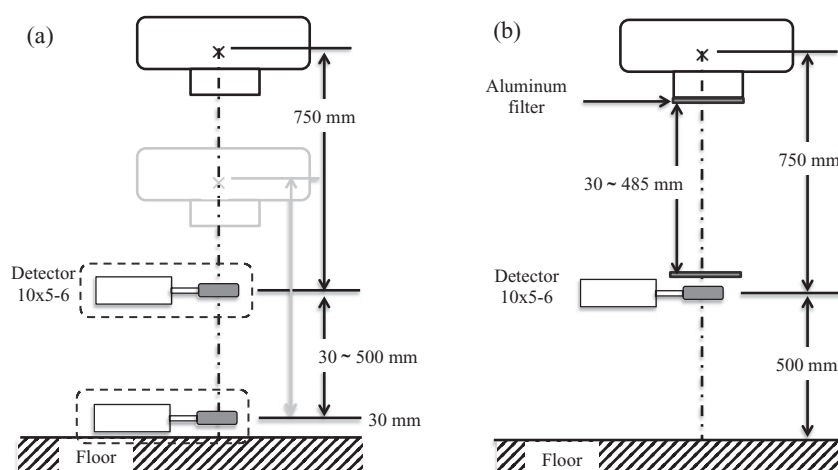
Figure 3. Setup for measurements evaluating the backscatter and side scatter. (a) Shows the measurement arrangement for backscatter, focus-detector distance is fixed (750 mm), floor-detector distance was varied between 30 and 500 mm. (b) Shows the measurement arrangement for side scatter, focus-detector distance is fixed (750 mm), floor-detector distance was fixed (500 mm), the distance of the Al plate was varied from 30 mm (closest distance to the detector) to 485 mm (movable diaphragm front).

tube. Therefore, we evaluated the correlation calculations and the actual measurement of the glass and acrylic plates in a Report 78 Spectrum Processor as the Al equivalent thickness. The glass used was six sheets of the nominal value of 0.7 mm thickness. The acrylic plates used were nominal value 1.5, 2.0 and 3.5 mm thickness plate. The total filtration of the industrial x-ray source device as 2.5 mm Al measures the Al attenuation curve. Next, we added a glass or acrylic plate on the total filtration. The total filtration is 2.5 mm Al + glass or 2.5 mm Al + acrylic. We measured each of the attenuation ratios. The Al equivalent thickness of a glass or acrylic plate was determined from the Al attenuation curve measured at 2.5 mm Al. Then, it was verified as an Al equivalent thickness of a glass or acrylic plate using a Report 78 Spectrum Processor based on the measured conditions.

3.2. Influence of backscatter and side scatter

The calculated value of the Report 78 Spectrum Processor was air kerma (μGy/mAs) at a distance of focus from 750 mm in vacuum. Therefore, backscatter and side scatter were minimized for the air kerma measurements of the diagnostic x-ray apparatus of interest. Backscattering was controlled by the floor-detector distance, and the impact of the side scattering was evaluated using the Al plate-detector distance.

The effect of backscattering was evaluated for the x-ray device using the diagnostic x-ray equipment, as shown in figure 3(a). The focus-detector distance was fixed to 750 mm, and the distance of the effective center of the $10 \times 5 - 6$ detector from the floor surface was set to 30, 50, 100, 200, 300, and 500 mm. The irradiation conditions were changed and the tube voltage values of 50, 80, and 120 kV, tube current of 200 mA and the irradiation time of 0.1 s were used. We confirmed that the tube voltage and the tube current did not vary using the AB-2015E (TORECK Co., Ltd, Japan) x-ray tube voltage tube current meter. Considering the effect on the stem of the detector, the radiation field was set to 60 mm $\times$ 80 mm in the detector plane.
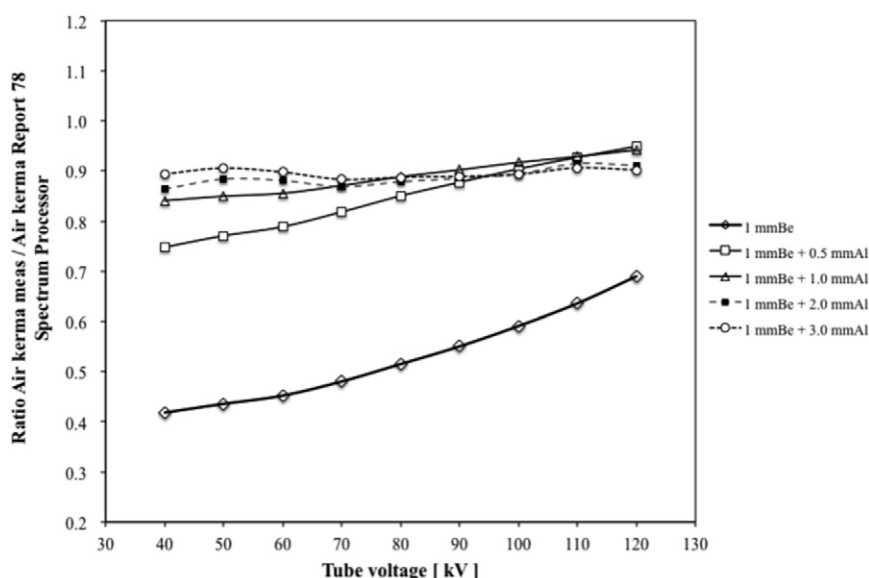
Figure 4. Ratio of the air kerma that was calculated by the air kerma and Report 78 Spectrum Processor as measured in each Al sheet thickness. Tube voltage (kV) on the horizontal axis. The vertical axis represents the ratio of air kerma that was calculated by the actual measured air kerma and that obtained by the Report 78 Spectrum Processor. Because L-characteristic x-rays from W appear without being attenuated for low tube voltage, it has been shown that the ratio is gradually decreased.

The effect of side scatter was evaluated using the experimental arrangement shown in figure 3(b). The x-ray tube was 750 mm away from the focal point, the $10 \times 5 - 6$ detector was fixed at a height 500 mm higher than the floor, and the effective center distance of the $10 \times 5 - 6$ Al plate was changed to 30, 50, 100, 200, 300, 400, and 485 mm. The distance at which the Al plate was directly attached to stop the x-ray irradiation was 485 mm. We used an Al plate with a nominal thickness of 1.0 mm.

3.3. Measurement of air kerma ratio due to diagnostic x-ray source device

Air kerma measurements were performed using the same dosimeter and detector as described in sections 3.1 and 3.2. Considering the results obtained in the experiments described in section 3.2, we used the following experimental setup: floor-detector distance of 500 mm, focus-detector distance of 750 mm, and the Al plate T was placed on the front of the movable diaphragm. The radiation field is set to 60×80 mm. The irradiation conditions were changed by varying the tube voltage in the range of 40–120 kV in 10 kV steps, and the tube current and the irradiation time were set to 200 mA and 0.1 s, respectively. When the tube current was 200 mA, the tube voltage pulsation rate was between 1.55% and 2.54% (Miyazaki *et al* 1994). The irradiation of each Al plate and measurements of the corresponding air kerma K'_x and K'_{x+T} were used to calculate the ratio R' for each tube voltage. We used the same nominal T values (0.5, 1.0, and 2.0 mm) as in section 3.1.

3.4. Measurement of the total filtration by IEC 60522

To obtain total filtration, IEC 60522 recommends 'x-ray tube assemblies with a nominal x-ray tube voltage exceeding 65, 75 kV, or approximately half the nominal x-ray tube voltage,
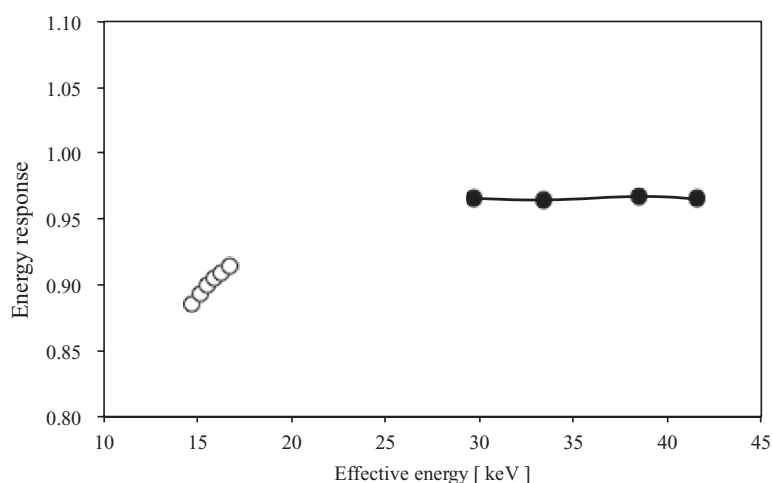
Figure 5. Energy response of the $10 \times 5 - 6$ detector and Model 9015 dosimeter. The horizontal axis represents effective energy (keV) and the vertical axis represents the energy response of $10 \times 5 - 6$. The black dotted line on the graph is the energy response measured by JQA. The white dotted line is the W target, and the energy response was evaluated by the x-ray source of the Al added filter of 0.5 mm at 24, 26, 28, 30, 32, and 35 kV conditions.

whichever is the greater. It is desirable to avoid testing close to the absorption edge of tungsten'. Therefore, to compare the total filtering values obtained with the proposed technique, we calculated the total filtration from the HVL_{1st} using the x-ray source device with the tube voltage of 75 kV in the apparatus described in sections 3.1 and 3.3. The total filtration of industrial x-ray equipment is necessary to obtain the nominal values of 1.0, 2.0, and 3.0 mm of the Al plate used in section 3.1. An Al attenuation plate for obtaining the HVL_{1st} is aligned separately from the Al plate used in the experiments described in sections 3.1 and 3.3 and was measured for every 0.1 mm. The thickness of the Al plate was evaluated as described in section 2.2. The measurement arrangement was the same as described in sections 3.1 and 3.3. In addition, the beam was collimated by a 5 mm thick Pb plate to eliminate the influence of side scatter from the Al attenuation plate.

4. Results and discussion

4.1. Report 78 Spectrum Processor of verification results

Figure 4 shows the plot of the ratio of K_x values calculated by the air kerma K_x and those obtained by the Report 78 Spectrum Processor in the Al plate x. For the industrial x-ray equipment, the total filtration is only because of the 1 mm thick Be window. Therefore, x can be evaluated as total filtration. We found that the ratios of the calculated and measured values are in good agreement for greater Al plate thicknesses. The ratios of the calculated and the measured values do not agree well in the case of thin Al plate, which is likely due to the L-characteristic x-rays generated from W. L-characteristic x-rays of the W target appear at 10.2, 11.5, and 12.1 keV (Hubbell and Seltzer 1995). If x is small, L-characteristic x-rays are not attenuated and become noticeable. In this case, while the value measured by the dosimeter does not reflect the impact of the L-characteristic x-rays, the calculated value considers the dose of the L-characteristic x-rays. The effects of L-characteristic x-ray are particularly conspicuous
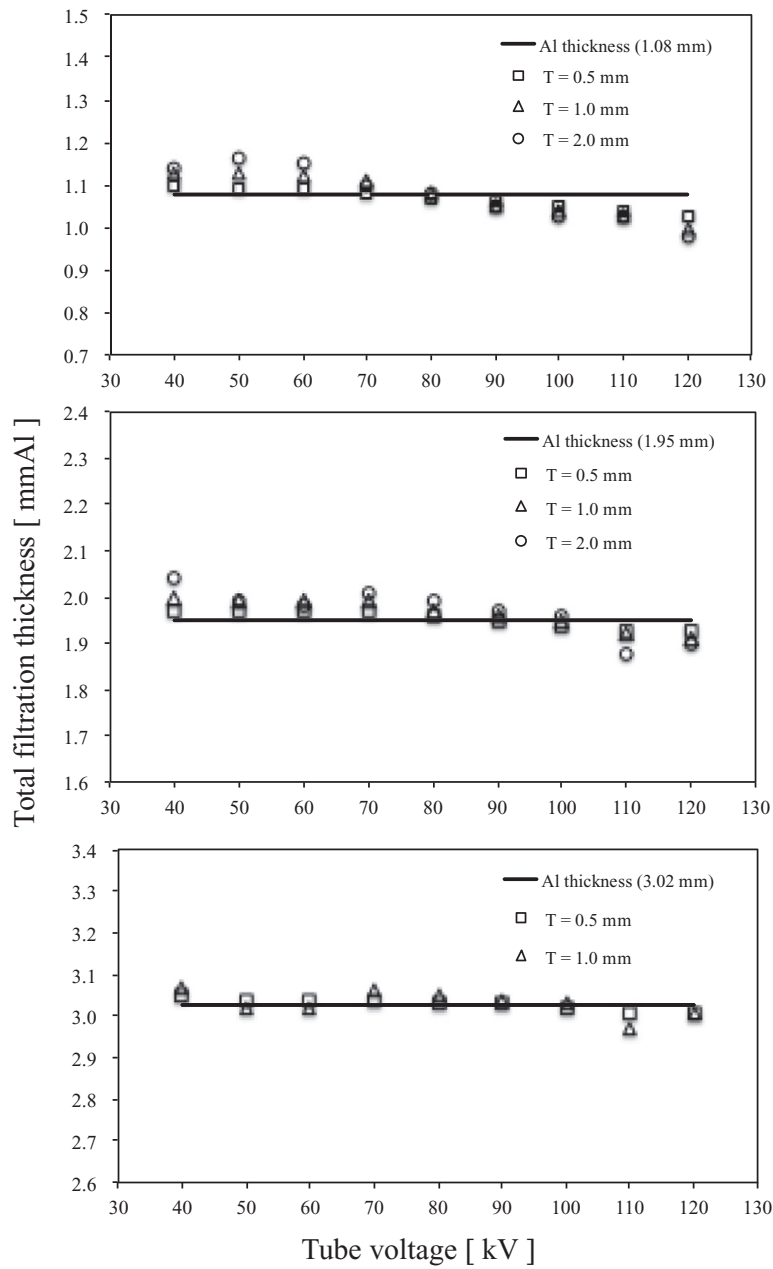
Figure 6. Total filtration thickness change of the respective tube voltages measured at ISOVOLT Titan E. The horizontal axis represents tube voltage (kV) and the vertical axis represents the total filtration thickness (mm Al). The topmost graph shows the total filtration of the nominal value 1.0 mm Al, the graph in the center shows the total filtration of the nominal value 2.0 mm Al, and the lowermost graph shows the total filtration of the nominal value of 3.0 mm Al. T indicates the additional filtration thickness showing that it is better to use the Al plate of about 0.5 mm.

Table 2. Al equivalent thickness of the glass and acrylic obtained from measurement and calculation.

Tube voltage (kV)			Glass thickness (mm)						Acrylic thickness (mm)		
			0.72	1.44	2.16	2.88	3.60	4.31	1.49	2.01	3.52
40	Measured[a]	(mm Al)	0.43	0.81	1.22	1.65	2.08	2.50	0.13	0.18	0.31
	Calculated[b]		0.43	0.80	1.21	1.64	2.07	2.49	0.13	0.18	0.31
50	Measured	(mm Al)	0.43	0.83	1.24	1.67	2.11	2.53	0.14	0.19	0.34
	Calculated		0.43	0.82	1.23	1.66	2.10	2.52	0.14	0.19	0.34
60	Measured	(mm Al)	0.43	0.84	1.25	1.69	2.13	2.56	0.15	0.21	0.36
	Calculated		0.43	0.83	1.24	1.68	2.12	2.55	0.15	0.20	0.36
70	Measured	(mm Al)	0.43	0.84	1.26	1.70	2.14	2.57	0.16	0.22	0.38
	Calculated		0.43	0.83	1.26	1.70	2.14	2.57	0.16	0.21	0.38
80	Measured	(mm Al)	0.43	0.85	1.27	1.71	2.16	2.60	0.17	0.23	0.41
	Calculated		0.43	0.84	1.27	1.71	2.16	2.60	0.17	0.23	0.40
90	Measured	(mm Al)	0.43	0.85	1.29	1.73	2.18	2.62	0.17	0.24	0.42
	Calculated		0.43	0.85	1.28	1.73	2.18	2.63	0.18	0.24	0.42
100	Measured	(mm Al)	0.43	0.86	1.30	1.74	2.19	2.64	0.18	0.25	0.43
	Calculated		0.43	0.86	1.30	1.75	2.20	2.65	0.19	0.25	0.45
110	Measured	(mm Al)	0.43	0.86	1.30	1.75	2.21	2.66	0.19	0.26	0.45
	Calculated		0.43	0.87	1.31	1.76	2.22	2.68	0.20	0.26	0.47
120	Measured	(mm Al)	0.43	0.86	1.31	1.76	2.22	2.68	0.19	0.27	0.47
	Calculated		0.44	0.87	1.32	1.78	2.24	2.70	0.21	0.27	0.49

[a] Measurements performed with the arrangement shown in figure 1. The total filtration of the industrial x-ray source device was performed as 2.5 mm Al.
[b] Calculation using the Report 78 Spectrum Processor.

at a low tube voltage. A dosimeter must be selected in consideration of the characteristics of the energy to be measured. The effective energy of tube voltage 40 kV of $x = 1.0$ mm Al is 15–20 keV. It shows the energy response of the detector $10 \times 5 - 6$ and dosimeter Model 9015 in figure 5. The energy response of the $10 \times 5 - 6$ detector would change the measured values by about ±10% depending on the energy region (Sekimoto 2015). Therefore, it is necessary to consider the response of the detector during the measurements. It is believed that dosimeters can be eliminated for measurements at around 15–20 keV, rather using a dosimeter for the mammography area than in the diagnostic region. In this study, the diagnostic x-ray source device is the target. The total filtration in this area is defined as greater than 2.5 mm of Al, and x is not problematic unless the x-ray source device is in the vicinity of 1.0 mm Al. The evaluation of total filtration due to x for an x-ray source device in the vicinity of 1.0 mm Al will be addressed in a future study.

The calculated results for total filtration at the tube voltages are shown in figure 6. It was found that the thickness T of the arbitrarily placed Al plate must be reduced in contrast to the results obtained by x. Systematic errors between x and $x+T$ decrease for small T values leading to an improved correlation between R' and R. Here, the T was obtained for the thinnest Al plate, 0.5 mm Al. Although small values of T are better for the evaluation of R, the accuracy is low for Al thicknesses smaller than 0.5 mm. Furthermore, a thinner Al plate is less expensive, and therefore, 0.5 mm is a reasonable choice for the Al plate thickness. The total filtration differences for different tube voltage for T values of 0.5 mm and Al plate thickness of 1.0, 2.0, and 3.0 mm Al were −4.37%–2.12%, −1.01%–1.04%, and −0.56%–0.76%, respectively. Based on these results, when the total filtration x is 2.0 mm Al above, and the thickness T of the
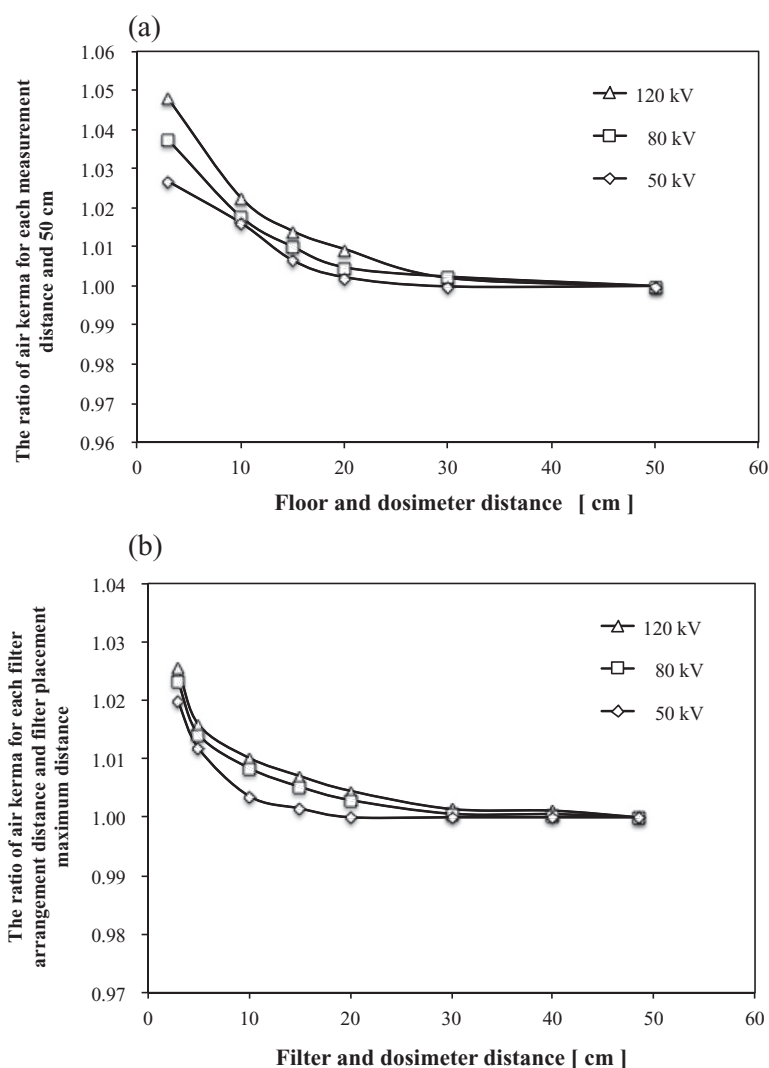
Figure 7. Result for backscatter and side scatter in the $10 \times 5 - 6$ detector. (a) Shows the results of the backscatter. The horizontal axis represents the distance between the detector and floor (cm); the vertical axis represents the kerma ratio. (b) Shows the results of the side scatter. The horizontal axis represents the distance between the detector and the Al filter (cm), and the ordinate represents the ratio between the measured value of the distance (48.5 cm) and the distance between the detector and the Al filter. Data for tube voltages of 50, 80, and 120 kV are shown. Backscatter and side scatter are considered to be negligible for separation distances greater than 30 cm.

Al plate which is placed in any of about 0.5 mm, the evaluation of the total filtration in terms of the Al equivalent can be performed accurately.

The results of the Al equivalent thickness of glass and acrylic is shown in table 2. The glass is within 1.3%, and the acrylic is within 6%, which was the result of the Al equivalent thickness obtained by measurement and calculation being the same. It can be said that it is possible to evaluate the total filtration of the results from the diagnostic x-ray source device by using a Report 78 Spectrum Processor as an Al equivalent thickness. Glass is an Al equivalent
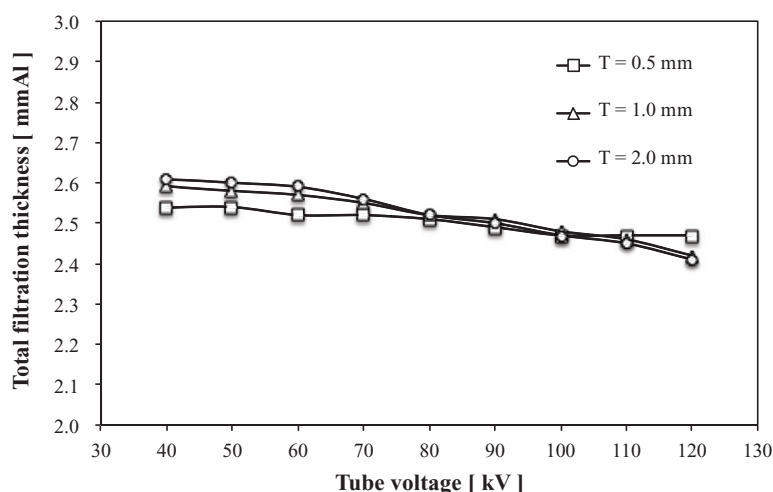
Figure 8. Total filtration thickness at each tube voltage measured at KXO-80G. Horizontal axis represents tube voltage (kV), and the vertical axis represents the total filtration thickness (mm Al). The nominal total filtration thickness of KXO-80G is 2.5 mm Al. The total filtration values in each tube voltage with $T = 0.5$ mm Al are $-1.21\% - 1.57\%$ against 2.5 mm Al.

thickness regardless and becomes almost the same as the x-ray energy. On the other hand, the acrylic thickened, as the x-ray energy is high. This study used a Report 78 Spectrum Processor. However, we propose that the same results would be obtained using in any other applicable software.

4.2. Measurement of the backscatter and side scatter

Results of the measurements performed to examine the effect of backscatter are shown in figure 7(a). Examination of figure 7(a) shows that the effect of backscatter can be ignored when the floor-detector distance from the floor is equal to or greater than 30 cm. The results of the measurement performed to examine the effects of side scatter are shown in figure 7(b). Here, as well, the results shows that side scatter can be ignored when the distance between the $10 \times 5 - 6$ detector and the Al plate is 30 cm or greater. However, while these results can be adapted to the case of using a $10 \times 5 - 6$ as the detector for the other detection sections (shape and size), the order may not be adapted; this factor must be considered.

4.3. Measurement of the total filtration through diagnostic x-ray equipment

The results of the total filtration value for each tube voltage of KXO-80G are shown in figure 8. Total filtration diagnostic x-ray apparatus of 2.5 mm Al was used in this experiment, where T values were 0.5, 1.0, and 2.0 mm. Results similar to T equal to section 4.1 were close to those of the thin Al plates as the total filtration 2.5 mm Al results were obtained. The total filtration difference values for different tube voltage values when using a 0.5 mm thick Al plate were -1.21%–1.57%. It is possible to obtain results from the evaluation of the total filtration rate for different tube voltage values using the proposed method.

An ionization chamber dosimeter was used for the air kerma measurements. It has good energy characteristics and calibration constants, especially if the diagnostic area is about $\pm 2\%$.
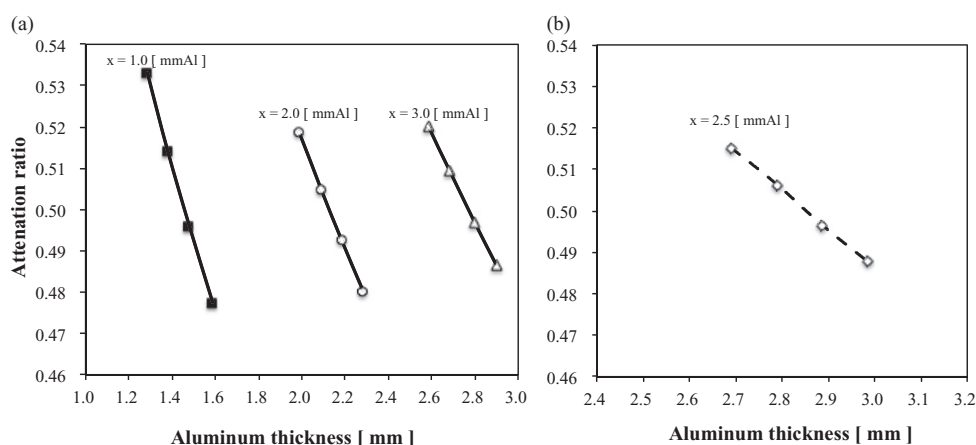
Figure 9. Total filtration of the measurement results by the IEC 60522. (a) Represents ISOVOLT Titan E, and (b) is the Al attenuation curve for the tube voltage of 75 kV of KXO-80G. Horizontal axis is the thickness of the Al attenuation plate (mm), and the vertical axis represents the attenuation ratio. (a) For ISOBOLT Titan E, HVL_{1st} obtains the total filtration of 1.0 mm Al for 1.46 mm, 2.0 mm Al for 2.13 mm, and 3.0 mm for 2.77 mm. In total filtration, 2.5 mm Al of (b) from KXO-80G, HVL_{1st} was 2.84 mm.

The results described in section 4.1 showed that for low tube voltages and thin total filtration the effect of L-characteristic x-rays from a W target is noticeable. This is only the case for the industrial x-ray device. However, for the x-ray apparatus used in the medical field, the total filtration is 2.5 mm Al or higher. Therefore, consideration of the L-characteristic x-rays is unnecessary. While low-cost semiconductor dosimeters are now widely available, their energy characteristics are not good. Therefore, when measuring air kerma using semiconductor dosimeters, it is necessary to obtain the calibration constants for each energy region. This will be the future direction of our study.

4.4. Measurement of the total filtration by IEC 60522

The Al attenuation curves obtained with ISOBOLT Titan E are presented in figure 9(a), and the Al attenuation curves obtained with KXO-80G are presented in figure 9(b). Because ISOBOLT Titan E has no diaphragm, the filter was inserted at any thickness in the total filtration. In figure 9(a), HVL_{1st} is 1.46 mm (error of 25.8%) at $x = 1.0$ mm Al, 2.13 mm (8.29%) at $x = 2.0$ mm Al and 2.77 mm (−9.46%) at $x = 3.0$ mm Al. In addition, figure 9(b) shows that KXO-80G total filtration was 2.5 mm Al for HVL_{1st} of 2.84 mm, with a difference of 11.9%. The total filtration differences between the calculated and the measured values obtained using the diagnostic x-ray source device were in the range of −1.21%–1.57%. The difference between the HVL methods has been conventionally performed and is 11.9%, and the method of the present study is therefore useful.

Conventional HVL methods are affected by backscatter and side scatter as well as the changes in the stability of the output of the x-ray source by the measuring arrangement. Especially when determining the attenuation curve, the large number of output x-rays leads to a large load on the x-ray tube. For the proposed method, it can be readily determined whether the 0.5 mm is the minimal total filtration thickness of the Al plate.

5. Conclusions

The total filtration of an x-ray source device is determined to correspond with the tube voltage changes by using the methods of the present study. The total filtration differences between the calculated values and the measured values obtained using the diagnostic x-ray source device were in the range of -1.21%–1.57%, which represents the best results of the filter thickness calculation approaches that have been evaluated to date. This method reduces the number of times irradiation takes place and is convenient because only one Al plate is used. Therefore, the x-ray tube load can be reduced, unlike in other methods where many x-ray tubes are needed. The new method provides the Al equivalent total filtration up to tube voltages in the 40–120 kV range and allows the user to conveniently perform the measurements by using a more appropriate dose and x-ray. Using the calculation of the entrance surface dose-calculation software and x-ray spectrum, it is possible to assess the spectral shape. In addition, when an x-ray source device is introduced, even the focus by the target of the x-ray tube can be evaluated by performing initial total filtration measurements. However, this approach of using an x-ray source device and a dosimeter to measure the air kerma must be performed considering the backscatter and side scatter arrangement, and it is necessary to consider the energy response of the detector in the measured energy region.

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