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Half-value Layer Measurement Method for Routine Management of Digital-breast-tomosynthesis-equipped Breast Radiography Systems

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With the increasing use of digital breast tomosynthesis imaging, the accuracy and quality control of mammography systems is gaining importance because of the need for high image stability and quality. We focused on the accuracy and quality control of mammography systems using digital breast tomosynthesis and proposed a simple method of maintaining and controlling the accuracy of half-value layer (HVL) measurements. The European Reference Protocol for the Quality Control of the Physical and Technical Aspects of Digital Breast Tomosynthesis Systems guidelines state that HVL measurements should be performed annually; however, this would not reveal daily changes in X-ray output. Changes in HVL are important indicators for determining changes in tube voltage and considering radiation doses associated with radiography. We investigated a simple control method to measure HVL by photographing an aluminium step for routine quality control of mammography systems. The proposed HVL measurement on the aluminium step enables HVL measurement for short-term control. Moreover, it is inexpensive and allows for a straightforward evaluation of X-ray quality. Thus, this method can be used for simpler routine equipment management as the presence or absence of fluctuations can be confirmed with a single image of the aluminium step and by determining the dose.

1. Introduction

Stable acquisition of high-quality images is required in mammography; thus, daily accuracy and quality control of mammography systems is important. In recent years, the use of digital breast tomosynthesis (DBT) has been increasing in imaging; therefore, in this study, we focused

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on the accuracy and quality control of mammography systems equipped with DBT. The half-value layer (HVL), one of the measures of quality control, is an important index when considering the exposure dose associated with radiography and it has a significant impact on exposure assessment. It is important to correctly evaluate and manage the radiation quality, which directly affects the tissue absorption conversion coefficient in the evaluation of the actual radiation dose received by the patient. In particular, the patient dose in mammography is controlled by the mean mammary dose (MGD), and HVL is indispensable for the calculation of MGD. Wagner *et al*. used a monitored dosimeter to reduce the effect of power fluctuation of the X-ray system as a method of accurately determining MGD in mammography.(1) Usually, an aluminium plate with a purity of 99.9% is used to measure HVL in mammography;(2–4) however, Barnes reported that the HVL depends on the purity of the aluminium plate and the measurement position.(5) In contrast, Ishii *et al*. reported that for quality control, HVL should be measured using the same part of the same plate in the same filter set.(6) The European Reference Protocol for the Quality Control of the Physical and Technical Aspects of Digital Breast Tomosynthesis Systems (EUREF) guidelines (version 1.01, 2016) state that HVL should be measured with the X-ray tube fixed.(7) However, in actual DBT imaging, the X-ray tube is moved in a circular arc during imaging; therefore, measuring HVL with a mammography system equipped with a DBT requires the use of the device's onboard control mode, making it difficult to easily perform daily measurement in clinical practice. Thus, we developed an aluminium step attenuation method using an aluminium step and receiver that enables measurement during DBT operation. With this method, the same part of the same plate of the same filter set can be easily measured, and we investigated whether HVL measurement can be performed even when the X-ray tube is in arc motion, which is assumed to be the case in clinical practice.

2. Materials and Methods

2.1 Aluminium step and receiver preparation using the aluminium attenuation method

2.1.1 Aluminium step

In conventional HVL measurements, after measuring the dose without aluminium plates, aluminium plates are inserted one by one, and the respective doses are measured. Therefore, the reproducibility of X-ray irradiation affects the measurements; however, if the measurement can be performed with a single irradiation, the reproducibility of the dose becomes a non-issue. Therefore, five aluminium steps were created by overlapping 0.1-mm-thick aluminium sheets of 99.9% (RMI 115H) and 99.5% (JIS H4000-A1050) purity to total thickness of 0.3–0.8 mm. A frame of the dimensions of 21 × 112 × 5 mm^3 was created using acrylic resin to fix the aluminium steps (Fig. 1). This enabled measurement with a single irradiation.

2.1.2 Receiver

The receiver was made of acrylic resin with the dimensions of 26 × 118 × 7 mm^3. Seven 15 × 15 × 4 mm^3 grooves were made on the inside to accommodate the dosimeter; each area was

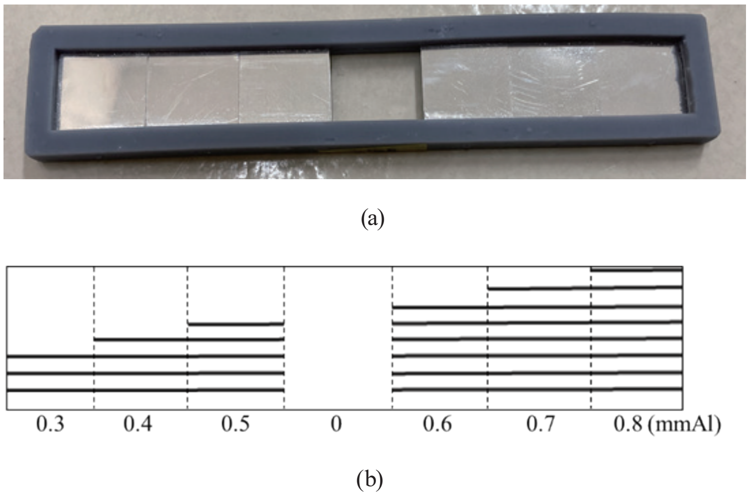

Fig. 1. (Color online) Aluminium step (99.5% purity). (a) Top view. (b) Side view.

surrounded by 1-mm-thick lead to create a narrowing effect of the X-ray irradiation field and prevent the generation of scattered rays (Fig. 2).

2.2 Measurement of the semivalent layer

2.2.1 HVL measurement by fixed method

An optically stimulated luminescence dosimeter (OSLD) was placed inside the receiver (Fig. 3), and HVL was calculated at a tube voltage of 31 kV using an aluminium step made of 99.9% purity aluminium. Equation (1) was used for the calculation.

An AMULET Innovality (Fujifilm Medical Co., Tokyo, Japan) X-ray mammography device and a nanoDot (Landauer Co., Glenwood, IL, USA) OSLD with a microStarii (Landauer Co.) OSLD reader was used. The X-ray tube swing angle was set to 0°, and continuous irradiation, similar to DBT imaging, was performed with the X-ray tube in the fixed irradiation mode. The aluminium step was placed 40 mm upward from the breast support and 60 mm from the breast wall edge. The number of measurements was set to five to examine the effect of the difference in dosimeters used on the semivalent layer. The tube current time product was 56 mAs, the target/filter was W/Al. The geometric arrangement is shown in Fig. 4.

$$HVL = \frac{X_1 \cdot \ln\left(\frac{2 \cdot Y_2}{Y_0}\right) - X_2 \cdot \ln\left(\frac{2 \cdot Y_1}{Y_0}\right)}{\ln\left(\frac{Y_2}{Y_1}\right)} \tag{1}$$

Y_0 : Absorbed dose without aluminium plate (absorbed doses for 0 mm aluminium thickness)
Y_1 : Absorbed dose slightly < $Y_0/2$
Y_2 : Absorbed slightly > $Y_0/2$

Fig. 2. (Color online) Receiver.

Fig. 3. (Color online) Layout of optically stimulated luminescence dosimeters.

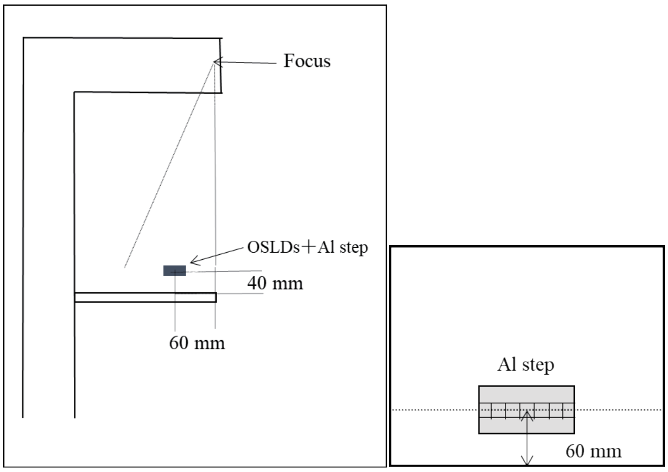

Fig. 4. Geometric arrangement.

X_1 : Aluminium plate thickness for Y_1
X_2 : Aluminium plate thickness for Y_2

2.2.2 HVL measurement by the transfer method

The OSLD was placed as described in Sect. 2.2.1, and HVL was calculated at a tube voltage of 31 kV using aluminium steps of 99.9 and 99.5% purity. Pulsed irradiation was performed while moving the X-ray tube in the DBT imaging mode with a swing angle of ±20°, and the aluminium step was placed 40 mm above the breast support and 60 mm from the breast wall edge. The tube current time product, target/filter, number of measurements, and calculation method were the same as those in HVL measurement by the fixed method.

2.2.3 HVL measurement by the standard measurement method

A Piranha semiconductor device (RTI Electronics, Mölndal, Sweden) was placed 40 mm above the breast support and 60 mm from the chest wall edge in a standard measurement following EUREF guidelines, and the X-ray flux was collimated with 2-mm-thick lead to match the size of the dosimeter detector. The tube current time product, target/filter, and number of measurements were the same as in HVL measurement by the fixed method, and the fixed X-ray tube irradiation mode was the same as that for DBT imaging with the X-ray tube fixed. The geometric arrangement is shown in Fig. 5.

3. Results

Figure 6 shows the measurements of absorbed doses for each aluminium thickness when using aluminium with 99.9% purity in the fixed method.

The absorbed dose for an aluminium thickness of 0 mm is $Y_0 = 8.764$ mGy. From this value, using Eq. (1), HVL for the fixed method is calculated to be 0.55 mmAl.

The absorbed dose measurements for each aluminium thickness when using aluminium with 99.9 and 99.5% purity with the transfer method are shown in Fig. 7.

The absorbed doses for 0 mm aluminium thickness were $Y_0 = 8.357$ mGy for 99.9% purity aluminium and $Y_0 = 8.273$ mGy for 99.5% purity aluminium; HVL was calculated from these values using Eq. (1). HVL for the transfer method was 0.54 and 0.52 mmAl for Al with 99.9%

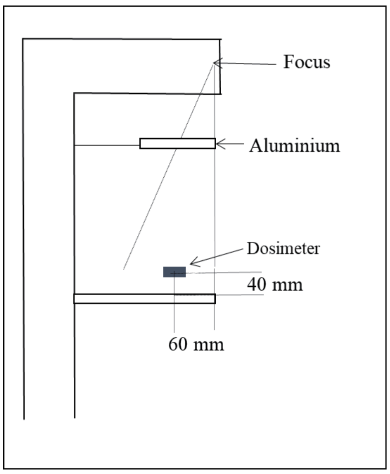

Fig. 5. Geometric arrangement.

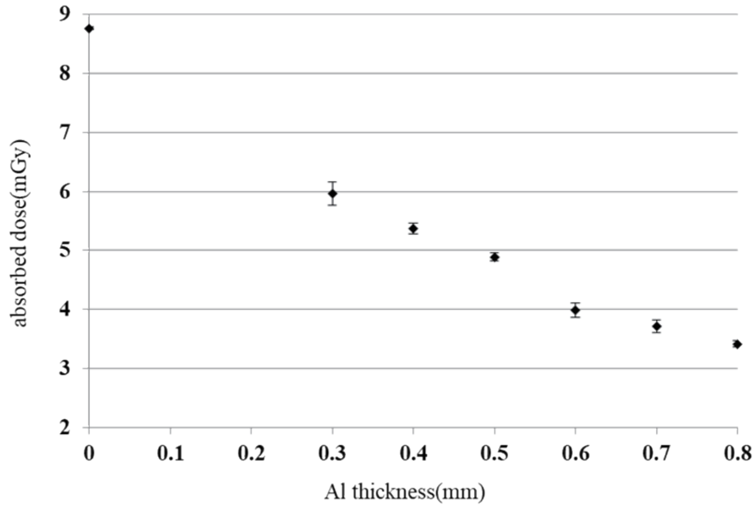

Fig. 6. Measured absorbed dose for each aluminium thickness using aluminium with 99.9% purity.

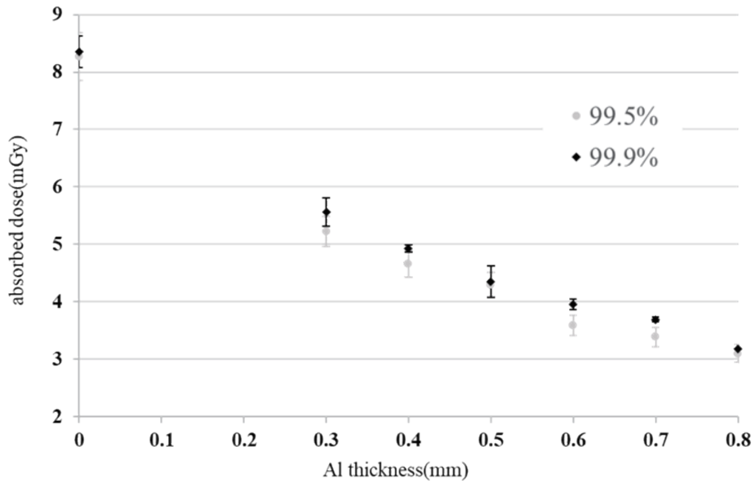

Fig. 7. Measured absorbed dose for each aluminium thickness using aluminium with 99.9 and 99.5% purity.

and 99.5% purity, respectively. HVL for the standard measurement method was 0.55. The HVL results for each method are shown in Table 1.

4. Discussion

HVL calculated using the 99.9% purity aluminium step devised in this study was 0.55 mmAl for the fixed method and 0.54 mmAl for the transfer method, the same as obtained for HVL using the standard measurement method and the fixed method. The semiconductor dosimeters used in this study were calibrated by the Measurement Center of the Japan Quality Assurance

Table 1
Half-value layer calculated using different measurement methods.

	Fixed method 99.9%	Transfer method 99.9%	Transfer method 99.5%	Standard measurement method
HVL (mmAl)	0.55	0.54	0.52	0.55

Organization. However, measurements obtained with semiconductor dosimeters are highly energy dependent,[8–10] and the X-ray flux hardens as the thickness of the aluminium plate increases. It is impossible to calibrate semiconductor dosimeters in response to minute changes in radiation quality, and it is necessary to perform cross-calibration for each aluminium plate thickness at the time of measurement using measurements from semiconductor dosimeters and ionization chamber dosimeters. The OSLDs used in this study must be calibrated in consideration of the energy dependence of the dosimeters in order to perform dosimetry,[11] and calibration was performed by the method of Takegami *et al.*[12] The IAEA Human Health Series[13] recommends that radiation-measuring instruments used for quality control of mammography should have energy dependence within ±5% and accuracy within ±5%. Kawaguchi also reported that OSLDs can be used to measure mammography doses within ±5% energy dependence and ±5% accuracy by calibrating the uniformity of each element and eliminating the effect of angular dependence; thus, they are useful OSLDs for mammography dosimetry.[14–16]

The EUREF guidelines recommend using aluminium with a purity of 99.9% or higher for the measurement of the semivalent layer. However, high-purity aluminium is expensive. Therefore, HVL was measured by creating an aluminium step using a low-cost 99.5% purity aluminium sheet. HVL was 0.55 mmAl for 99.9% purity and 0.52 mmAl for 99.5% purity, indicating that HVL of 99.5% purity aluminium will be lower than for 99.9% purity aluminium. This is due to the fact that HVL of the 99.5% purity aluminium sheet is about 7.5% lower than that of the 99.9% purity aluminium sheet, as reported in a previous study,[5] because in addition to aluminium, there are trace amounts of Si, Fe, Cu, Mn, Mg, and Zn in the alloy. However, since 99.5% purity aluminium is inexpensive and easy to purchase, it is suggested that the 99.5% purity aluminium employed in this study can be useful for periodic HVL measurements in quality control with the use of a correction factor for the difference in HVL. In addition, the use of the aluminium step suggests that the semivalent layer can be calculated more easily because the aluminium plates are stacked and fixed, the same filter set can always be used, and the measurement can be performed with a single irradiation. However, when semiconductor dosimeters or OSLDs are used for quality control, it is preferable to always use the same dosimeter and the same filter set.

According to the EUREF guidelines, the X-ray tube should be fixed for measurement. However, the X-ray tube is not used in a fixed position in clinical practice; moreover, some devices do not have a quality control mode and cannot irradiate X-rays in the same way as in DBT imaging with the X-ray tube in a fixed position. Therefore, HVL was obtained using the moving method, in which the X-ray irradiation is the same as that in DBT imaging, using an aluminium step. The obtained HVL was smaller than those obtained by the fixed method and the standard measurement method. This is because X-rays enter the aluminium plate

Fig. 8. Weakening of X-rays with oblique incidence. (a) X-rays enter the aluminium plate perpendicularly. (b) X-rays enter the aluminium plate obliquely.

perpendicularly when the X-ray tube is stationary, as shown in Fig. 8(a), but when the X-ray tube is moved, X-rays enter the aluminium plate obliquely, as shown in Fig. 8(b). Therefore, the thickness of aluminium through which transmission actually occurs is larger than the original thickness, which is why HVL is smaller than that obtained by the standard method. Al step with the fixed method could provide accurately measured HVL, but the transfer method resulted in errors. In quality control, it is important to observe and notice changes in measurements over time. Having an understanding of the errors, using this Al-step facilitates management. For accurate HVL measurements, it is necessary to use aluminium with a purity of 99.9% in the fixed method.

The receiver used in this study was made with a 5-mm-high lead wall. In DBT, the motion of the X-ray tube causes shadows of the lead septum. In the future, it will be necessary to consider the height and width of the lead receiver in accordance with the swing angle of the device. Although the receiver was made to match the swing angle of the device used in this study, detailed verification of the shape of the receiver for devices with different swing angles is a subject for future studies.

5. Limitations

The DBT mode of the mammography system used in this study has two modes: ±20° swing angle and ±7.5° swing angle. For a 5-mm-high lead bulkhead, a swing of ±7.5° affects the dose by up to 0.66 mm, and a swing of ±20° affects the dose by up to 1.82 mm. The height of the lead wall of the receiver may interfere with measurements at larger angles of swing of the X-ray tube.

6. Conclusions

The method developed in this study requires the preparation of an aluminium step and receiver as a preliminary step. However, once these preparations are made, this method is very simple and can obtain the semivalent layer with a single irradiation. In addition, although the EUREF guidelines[7] state that HVL measurements should be performed every year, the presence or absence of fluctuations can be checked simply by taking a single image of the aluminium step and determining the dose, suggesting that routine equipment management can be simplified.

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