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Determination of half value layers of X-ray equipment using computed radiography imaging plates

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Abstract A method for determining half value layers (HVLs) of inverter-type X-ray equipment using a computed radiography (CR) systems was developed. This method is similar to the traditional method, where the air kerma (K) is measured using an ionization based dosimeter and increasing aluminum (Al) absorber thickness, but utilized an imaging plate (IP) and the sensitivity index (S number) of the CR system as the dosimeter and the dosimeter reading, respectively. The IP and the S number were calibrated using an ionization chamber having traceability to the National Standard Ionization Chamber. A modified version of the S number definition equation $K = a \times S^{-b}$ was used to translate the S number to K values for X-ray beams produced using tube voltages ranging from 50 to 120 kV and additional Al filtration up to 2.5 mm. The coefficient 'a' varied depending on the beam quality, while the coefficient 'b' showed a constant value of 0.991. The HVLs in the range from 1.8 to 5.5 mm Al that were obtained with this method were in good agreement with those obtained with the traditional method, as uncertainties were between −7 and 4%. This method can be used to determine the HVLs of inverter-type X-ray equipment within an acceptable accuracy.

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Introduction

A diagnostic X-ray beam is characterized by the X-ray output and the beam quality [1]. The X-ray output is expressed in terms of the air kerma (K) per unit tube loading (mAs) at a specified distance from the tube focus whereas the beam quality is expressed in terms of half value layer (HVL). The HVL is the thickness of the aluminum (Al) absorber that is required to reduce the output to half of its initial value.

The determination of these two parameters is very important for quality control of the X-ray equipment and patient dose estimation. X-ray output and beam quality are dependent on the tube voltage settings and the total filtration of the tube. With increasing tube voltage settings both output and HVL increase, while with increasing total filtration the HVL increases but the output decreases. The impact of increased filtration on image quality, tube loading, and patient effective dose have been reported by Behrman et al. [2,3].

Most of X-ray examinations are routinely conducted at tube voltages ranging from 50 to 120 kV and total Al equivalent filtration ranging from 2.5 to 4.0 mm [2]. The respective HVLs of the X-ray beams used for routine diagnostic examinations range from 1.8 to 5.5 mm Al [3]. A previous survey on patient entrance skin doses during routine diagnostic examinations carried out in Japan revealed that doses range from 0.05 to 8.6 mGy [4]. These skin dose values corresponded to air kerma values at the imaging detector surface that range from 34 μ Gy to 3.4 mGy (routine air kerma range), respectively, when the focus-detector distance is 120 cm. Note that these air kerma values refer to the primary beam intensity and concern those areas of the imaging detector which are not covered by the patient anatomic structures.

The traditional method for determining the X-ray output and HVL uses ionization chamber based dosimeters [1,5,6]. However, in a recent study it was revealed that a computed radiography (CR) system can be used for measuring air kerma values in the range from 3.1 μ Gy to 0.17 mGy within an uncertainty of $\pm 5\%$ [7]. CR systems use imaging plates (IP) as detectors and the last years are gradually replacing the traditional screen-film systems worldwide [8]. Therefore, for those installations equipped with a CR system, the X-ray beam output, and patient dose measurements could be also carried out using the CR system.

The purpose of this study is to investigate whether CR system could be used to determine the HVL of the X-ray beam with an accuracy comparable to the traditional method.

Materials and methods

X-ray equipment and CR system

The X-ray equipment used in this study consisted of an inverter-type high voltage generator (DHF-158HII, Hitachi medico Co., Ltd.), and X-ray tube (UH6GC31E, Hitachi medico Co., Ltd.) and a collimator (ZUL5TYE, Hitachi medico Co., Ltd.). The inherent filtrations of the X-ray tube assembly and the collimator were equivalent to 1.0 and 1.5 mm Al, respectively, at a tube voltage of 70 kV.

The CR system (Fuji Photo Film Co., Ltd.) was composed by a set of IP plates (ST-VI_N, Fuji Photo Film Co., Ltd.) using BaFBr(I):Eu as storage phosphor, a reader (FCR Speedia, Fuji Photo Film Co., Ltd.), and a console unit (CR Console, Fuji Photo Film Co., Ltd.). The pixel size of the IP images was 150 μ m $\times$ 150 μ m.

Deriving air kerma and transmission ratio from S

The Fuji CR system uses as an exposure indicator the S number (S). The relationship between the air kerma (K) incident on the IP and the S number is inversely proportional [9]. The S number has been adjusted by the manufacturer, so as to be equal to 400 for an air kerma of 4.38 μ Gy (0.5 mR, $W/e = 33.97$ J/C). The relationship between K and S is represented by the following equation which is strictly valid only for an X-ray beam produced using a tube voltage of 80 kV and a total filtration of 3.0 mm Al [9]:

$$K = 1752 S^{-1} \quad (1)$$

For different tube potential values and total filtrations it has been seen in a previous study [7] that the K can be derived by the S number with an uncertainty of $\pm 5\%$ using the following modified version of Eq. (1):

$$K = a \times S^{-b} \quad (2)$$

It has been seen that for the tube potential and filtrations routinely used in clinical practice, the coefficient ' a ' decreases with increasing the tube potential and filtration, whereas the coefficient ' b ' remains approximately constant for all beam qualities [7].

The transmission ratio R_i for absorber thickness X_i is obtained by normalizing the air kerma value K_i after transmitting absorber thickness X_i to the air kerma value for zero absorber thickness K_0 as follows:

$$R_i = K_i \times K_0^{-1} \quad (3)$$

where K_i is $a_i \times S_i^{-b}$, and K_0 is $a_0 \times S_0^{-b}$.

The R_i is represented by using the S, coefficients ' a ' and ' b ' of Eq. (2) as follows:

$$R_i = a_i \times a_0^{-1} \times S_i^{-b} \times S_0^b \quad (4)$$

Thus, the R_i can be expressed using the S.

Measurement

Measurement setup

Figure 1 shows the layout of the geometrical setup used for K measurements using the ionization chamber and the IP methods. The IP was calibrated against a 2.46 cm in diameter and 3.84 cm long chamber (Radcal 9015, 10 $\times$ 5–6) which was on its turn calibrated against the standard at Secondary Standard Dosimetry Laboratory in the range of effective energy from 20 to 50 keV [10]. Absorbers from 0 to 11 mm thick Aluminum (purity of 99.999%, Nilaco Co., Ltd.) were set on the lead mask placed at 48 cm from the focal point. The focus-detector distance (FDD) was set at 120 cm. An 8 cm $\times$ 8 cm exposure field included a 5 cm $\times$ 5 cm CR scan area on the IP or the 2.46 cm $\times$ 3.84 cm ionization chamber. The chamber was placed 60 cm above the floor in order to provide measurement of free-in-air exposure.

Figure 1 Layout of air kerma measurement. (a) Ionization chamber, and (b) IP.

Dosimeter readings were corrected for temperature and pressure. The IP was placed on a polystyrene box. Preliminary experiments showed that the backscatter from the polystyrene box had no effect on the S number.

Transmission curve

Transmission curves for 64 combinations of tube voltages and additional filtrations were derived using the K values measured with the ionization chamber and the IP for eight values of tube voltages (50, 60, 70, 80, 90, 100, 110, and 120 kV) and eight values of additional filtration (0, 0.2, 0.4, 0.6, 1.0, 1.5, 2.0, and 2.5 mm Al) using Al absorbers with thickness ranging from 0 to 11 mm. Exposure time was set at 50 ms and tube current values were adjusted from 20 to 100 mA for each one of the 64 combinations of tube voltage and additional filtration used. The ionization chamber was irradiated five times under the same conditions for reproducibility testing purposes and for the same reason five IPs were sequentially irradiated. IPs were read within 4 min $\pm$ 5 s after irradiation at a temperature of 26.0 ± 1.0 °C in order to suppress fading effect within an uncertainty of $\pm 0.1\%$ [7]. For these repeated exposures it was verified using the ionization chamber and a calibrated kilovolt peak meter that both the air kerma and the tube voltages remained constant within an uncertainty of $\pm 1\%$.

Determination of HVL with ionization chamber and IP

Sixty four HVLs were determined by using the 64 relative transmission curves that were obtained from the transmission curves by normalization to the K values measured for zero absorber thickness. This was done in accordance with the interpolation method using a least square logarithmic fit to four data points at two absorber thicknesses on either side of the HVL [11]. The HVLs determined by

using the S number (HVL_{IP}) were compared with those determined with the ionization chamber (HVL_{ch}). Uncertainty of the HVL_{IP} was calculated by using the relative discrepancy $100(HVL_{IP} - HVL_{ch})/HVL_{ch}\%$ between the HVL_{ch} and the HVL_{IP} .

Results

Figure 2 shows the relationship between the coefficient ' a ' (y-axis) of Eq. (2) and the Al absorber thickness (x-axis) when ' b ' was 0.991 for tube voltages ranging from 50 to 120 kV and zero additional filtration. This value of ' b ' was found to produce the best fitting results in all combinations of tube voltages and additional filtrations. The relationship at each tube voltage was represented by a quadratic function given in Fig. 2. Coefficients ' a ' decreased when the absorber thickness was increased. Coefficients ' a ' at the same absorber thicknesses decreased as the voltage increased. Coefficients ' a ' at 90, 100, 110, and 120 kV coincided with each other within an uncertainty of $\pm 5\%$ in an absorber thickness region beyond 2 mm Al. The correlation coefficients (r^2) of the eight quadratic functions were larger than 0.98 at all tube voltages.

Figure 3 compares two transmission curves of the air kerma at 80 kV without additional filtration obtained by using an ionization chamber and an IP. Air kerma values approximated with Eq. (2) coincided with those measured with the chamber within an uncertainty of $\pm 5\%$.

Figure 4 presents the relative transmission curves at a tube voltage of 80 kV that were obtained using the data shown in Fig. 3. The curve corresponding to the IP method was calculated using Eq. (4), whereas the curve corresponding to the ionization chamber was calculated by dividing the air kerma values measured with the absorbers

Figure 2 Dependency of coefficient 'a' on absorber thicknesses and tube voltage when coefficient 'b' is 0.991.

by the air kerma value measured without absorber. The uncertainties of the relative transmission values obtained by using the ionization chamber and the IP method were less than $\pm 1.0\%$ and $\pm 5.0\%$, respectively. The relative transmission values derived with the IP method coincided with those derived using the ionization chamber within an uncertainty of $\pm 5\%$.

In Fig. 5 are compared the HVL_{ch} and HVL_{IP} that were calculated for the 64 combinations of eight tube voltages and eight additional filtrations. The HVL_{ch} ranged from 1.8 to 5.5 mm Al, and the HVL_{IP} ranged from 1.8 to 5.4 mm Al. An ideal line with a slope of 1 through the origin represents the line where HVL_{IP} completely coincides with HVL_{ch} . The HVL_{IP} were distributed around the ideal line in the HVL_{ch} less than 4.1 mm Al, but showed smaller values than the ideal one beyond 4.1 mm Al.

Figure 6 represents relative discrepancies between the HVL_{ch} and the HVL_{IP} for the 64 combinations. The relative discrepancies of the HVL_{IP} to the HVL_{ch} ranged from -5 to 4% between 1.8 and 3.6 mm Al of the HVL_{ch} , while those were distributed between -7 and 4% for all the HVL_{ch} .

Figure 3 Transmission curves of air kerma obtained with ionization chamber and IP. Air kerma values were measured with an ionization chamber, and calculated with the modified Eq. (2). Tube voltage: 80 kV, Additional filtration: 0 mm Al.

Discussion

The uncertainty of the HVL_{IP} determined by using an IP was distributed between -7 and 4% as shown in Fig. 6. This uncertainty obtained with modified Eq. (2) was comparable to that of $\pm 5\%$ obtained with an ionization chamber as reported by Gilmore.[12] Therefore, the accuracy of the IP method for determining the HVL values should be considered acceptable for quality control purposes.

The output of X-ray equipment is generally characterized by the output, or the air kerma per mAs at a specified distance and the beam quality in terms of HVL [6]. A method for measuring the air kerma by using IP (IP dosimetry) for inverter-type X-ray equipment was devised and presented in a previous report [7]. In the present study, this method was further developed to extend its applicability to the measurement of HVL. The results of this study confirm that IP dosimetry can be used to fully determine both the air kerma and the HVL of inverter-type X-ray equipment.

The HVLs of inverter-type X-ray equipment combined with a Fuji's CR system were determined by using the sensitivity index, or S number. However, this method is

Figure 4 Relative transmission curves obtained by normalizing the transmission curves in Fig. 3 to the 0 absorber thickness.

Figure 5 Comparison between HVL_{ch} and HVL_{IP} . HVL_{ch} , HVL determined with the ionization chamber; HVL_{IP} , HVL determined with IP using the modified equation. Ideal line, A line where HVL_{IP} completely coincides with HVL_{ch} . HVL_{ch} and HVL_{IP} were determined for 64 combinations of 8 tube voltages of 50, 60, 70, 80, 90, 100, 110, and 120 kV, and 8 additional filtrations of 0, 0.2, 0.4, 0.6, 1.0, 1.5, 2.0, and 2.5 mm Al.

applicable only in those Fuji CR systems that have been properly calibrated. The applicability of this method in other commercially CR systems needs further evaluation.

There are commercially available dosimeters with semiconductor detectors that can be used to determine HVLs by a single exposure without using aluminum absorbers within an uncertainty of $\pm 10\%$ or ± 0.3 mm Al.[13] These specific semiconductor dosimeters offer the simplest method for HVL measurement since both the ionization chamber and IP methods require at least three measurements (one without absorber and two with absorber thicknesses of one just above and one just below 50% for producing relative transmission values) to determine the HVL at any specific tube potential

Figure 6 Relative discrepancies between HVL_{ch} and HVL_{IP} . HVL_{ch} , HVL determined with the ionization chamber. HVL_{IP} , HVL determined with IP using the modified equation. Relative discrepancies were determined for 64 combinations of 8 tube voltages of 50, 60, 70, 80, 90, 100, 110 and 120 kV, and 8 additional filtrations of 0, 0.2, 0.4, 0.6, 1.0, 1.5, 2.0, and 2.5 mm Al.

value. Generally, the use of ionization chamber for determining the HVL requires drawing transmission curves by using measurements of more than four absorber thicknesses [11]. Therefore, the ionization chamber and IP methods are time-consuming when compared with these special semiconductor dosimeters and are inferior from the standpoint of convenience. On the contrary, in terms of accuracy, the ionization chamber and IP methods are superior to these semiconductor dosimeters. Therefore, to enhance the applicability of the IP dosimetry in the routine measurement of HVL, a method for determining HVL using a single exposure should be devised.

Conclusion

A method for determining the HVL of inverter-type X-ray equipment using an IP of CR system was developed. The HVLs from 1.8 to 5.5 mm Al can be determined within an uncertainty between -7 and 4% by using the modified equation. The accuracy of this method is comparable to that of traditional method using an ionization chamber.

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