Evaluation of X-Ray Beam Quality Based On Measurement and Estimations Using SpekCalc and IPEM78 Models

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Abstract

**Background:** Different computational methods have been used for the prediction of x-ray spectra and beam quality in diagnostic radiology. The purpose of this study is to compare the x-ray beam quality based on HVLs that had been determined through measurements and computational models estimations.

**Method:** The estimation of half value layers (HVLs) by IPEM78 (Spectrum Processor of the Institute of Physics and Engineering in Medicine's Report 78) and SpekCalc softwares were compared with that determined through measurements. In this study, the HVLs of diagnostic range x-ray 50 kVp to 120 kVp of both Philips (Phil) and GE x-ray machines were evaluated.

**Results:** SpekCalc and IPEM78 showed a maximum of 10% and 9% differences compared to measurements in the estimation of HVLs respectively. Both models showed that the percentage differences of means and standard deviations are within 5% respectively in the determination of HVLs over GE and Phil machines.

**Conclusion:** Both the computational models give an alternative method to estimate the HVLs for diagnostic range x-ray. These models are user-friendly in predicting HVLs that used to characterize the beam quality of the kilovoltage x-ray beam and provide prediction almost instantly compared to the experimental measurement which is time-consuming.

**Keywords:** beam quality, HVL, SpekCalc, IPEM78

Introduction

X-rays have an important impact in the modern technology especially for medical imaging purpose. Medical ionising radiation sources provide the largest contribution to the population dose from artificial sources and most of this contribution comes from diagnostic x-rays (1). X-ray spectrum and beam qualities are must-known parameters to study the dosimetric properties of the x-ray beam in diagnostic radiology. In order to complete describe the x-ray beam spectrum, the spectral photon fluence needs to be known. A spectrometer is needed but a spectrometry is too expensive and time-consuming for many routine applications of x-rays. Hence, half-value layer (HVL) is often used to describe the beam quality of kilovoltage x-ray. It is the thickness of materials required to reduce the intensity of an x-ray or gamma-ray beam to one-half of its initial value (2-3). In kilovoltage x-ray, the determination of the HVL of the x-ray beam is one of the ways to characterize the effective energy, by converting the HVL to the linear attenuation coefficient or mass attenuation coefficient. The effective energy of a polyenergetic beam is the energy of the x-ray in a monoenergetic beam which is attenuated at the same rate as the polyenergetic beam (4). It is used to describe the penetration of polyenergetic x-ray.
The direct measurement of x-ray spectra required expensive equipments and careful attention and planning during the experimental measurement setup, which is generally not practically in clinical diagnostic radiology department with limited physicists support. Since direct measurement is time-consuming and remains a difficult task, attempt for prediction of x-ray spectra in different energy range and various target/filter combination in diagnostic radiology have begun several decades ago and still represent an active research area. A detailed knowledge of x-ray spectra is required for the mathematical modeling and optimization of imaging systems in diagnostic radiology. Generally the x-ray prediction models can be divided into three categories. Empirical models are based on the use of measured data for prediction of x-ray spectra. Semi-empirical models are based on a theoretical formulation to calculate the x-ray spectra by mathematical derivation followed by some tuning in the equations’ parameters using measured data (5). IPEM78 (Spectrum Processor of the Institute of Physics and Engineering in Medicine’s Report 78) is one of the softwares that simulates the x-ray spectra using semi-empirical model and based on Birch and Marshal Model (6). It results in higher transmission curves compared with the measured spectra for all tube voltages and the differences increase with tube voltage. SpekCalc is a software programme used to calculate x-ray spectra from tungsten anode x-ray tube. It is relies on deterministic equations for bremsstrahlung productions, combined with numerically pre-calculated electron distributions (7).

The purpose of this study is to compare the results of IPEM78 (semi-empirical model) and SpekCalc (deterministic model) in HVL estimations with that determined from measurements. These two x-ray prediction models were evaluated as alternative and prompt method to determine x-ray beam quality in clinical environment. The determined HVLs were compared because it is the parameter used to describe the quality of the x-ray spectrum. The effective energies for the range of x-ray energy peak of 50 kVp to 125 kVp were also determined based on the linear attenuation coefficients determined experimentally.

Materials and Methods

Materials

This study was carried out with Phil x-ray machine SRO 33 100 (with ROT 350 Optimus 80 kW high frequency generator) and GE x-ray machine model 2336058 (with housing 46-15540VG48 and MPH 50 high frequency generator). The Phil machine has an anode angle of 13°. The permanent filtration inside the x-ray tube is 0.66 mm aluminium equivalent and for the tube housing is 2.5 mm aluminium equivalent and the additional filtration is 2.0 mm aluminium. The GE x-ray machine has an anode angle of 13°. The inherent filtration inside the tube is 0.8 mm aluminium equivalent at 150 kV and for the tube housing is 0.3 mm aluminium equivalent at 150 kV. The filtration inside the collimator is 1.5 mm aluminium equivalent at 80 kV.

SpekCalc software was used for the calculation of x-ray spectra. The spectra are presented for tungsten targets at tube voltages from 40 kV to 300 kV and target angles of maximum 90° with respect to the beam axis. The energy interval can be customized by the user. SpekCalc Graphical User Interface (GUI) is shown in Figure 1. IPEM78 uses XCOM programme to calculate linear attenuation coefficients for various materials and contains sets of radiology and mammography x-ray spectra with much wider ranges (6). These spectra are presented for tungsten targets at tube voltages from 30 kV to 150 kV and target angles from 6° to 22°. Different materials can be chosen as additional filters. All spectra are provided at an energy interval of 0.5 keV. Voltage ripple is an input parameter for IPEM78. The IPEM78 GUI is shown in Figure 2.

Measurement of HVL

Rad-Check Plus x-ray exposure meter (Model 06-526-2200) was used as the dosimeter to measure the output of the x-ray machines. Aluminium attenuator of 10 cm x 10
cm with thickness 0.5 mm and 1.0 mm were used in this study. The density of the aluminium attenuator is 2.699 g/cm$^3$.

The Rad-Check Plus exposure meter was positioned 100 cm perpendicular to the x-ray tube. The internal chamber of the Rad-Check Plus exposure meter is fully collimated within the x-ray field and was positioned in the center of the 10 cm × 10 cm field as shown in Figure 3. The first measurement was done without the aluminium attenuator. Then, it was repeated with 0.5 mm aluminium attenuator in place between the x-ray tube and the exposure meter. The exposure was repeated with the increment of 0.5 mm aluminium thickness until their values enclosed to the expected HVL value. The exposure measurement was then repeated for the range of peak energy from 50 kVp to 125 kVp. A final exposure without aluminium attenuator was repeated for every voltage to confirm the output stability of less than 2% from the first exposure without aluminium attenuator. A relative intensity of the x-ray beam to the exposure without aluminium attenuator versus aluminium attenuator thickness for every tube voltage was plotted on a semi-log graphs as shown in Figure 4 and Figure 5 for both GE and Phil machines.

**Determination of the Linear Attenuation Coefficient (µ) and the HVL**

The linear attenuation coefficient (µ) of aluminium for the corresponding tube voltage was determined by plotting a best-fit line by using Graphpad Prism 5 as shown in Figure 4 and 5. The HVL was determined by using the linear attenuation coefficient (µ).

**Determination of the Effective Energy**

The effective energy of the x-ray machine was determined from the linear attenuation coefficient, µ of the aluminium attenuator for various voltages by using the data from NIST (National Institute of Standards and Technology) as shown in Figure 6 (8). Later, the effective energy of both broad and fine focuses of the GE and Phil x-ray machines were compared.

**Evaluation of Spekcalc and IPEM78 for HVL Estimations**

The x-ray spectra calculated by the SpekCalc and IPEM78 models were evaluated through comparison with the measured spectra. The HVL values were used to compare with the measured HVL. Since the beam quality are a function of tube voltage, filtration and anode angle, the different computational models were used to simulate the spectra with the same parameters used in the measurements. The beam quality determined by the measurement was taken as the standard. The mean HVL ratios for all tube voltages under this study for both Phil and GE machines were calculated and standard deviations were determined. The mean HVL ratios for both broad and fine focuses of these two machines used for accuracy comparison of SpekCalc and IPEM78 models were calculated and then standard deviations were determined respectively.

**Results**

**Comparison of Effective Energy**

The HVLs determined from measurement were used to determine effective energies. The determined effective energies were summarized in Table 1. The effective energies of Phil machine were higher than that of GE machine for all the diagnostic range tube voltages. Most of the effective energies of broad focus were slightly lower than that of fine focus for both machines.

**Evaluation of Spekcalc and IPEM78 for HVL Estimations**

The HVL ratios as calculated by the computational models to the experimental measurements in estimating the beam qualities for the range of tube voltages 50 kVp -125 kVp under study were used for comparison between HVL estimations using SpekCalc and
IPEM78 models for both Phil and GE x-ray machines as tabulated in Table 2. SpekCalc showed a maximum of 10% difference for 50 kVp tube voltage compared to the estimated HVL based on measurement for Phil machine. Similarly, IPEM78 showed a maximum of 9% difference for 50 kVp and 81 kVp of the Phil and GE machines respectively in HVL estimations. All the means of HVL ratios for both the Phil and GE x-ray machines for tube voltages studied were less than 5% difference except the estimation by IPEM78 for broad focus of GE x-ray machine had shown a difference of 6%. The standard deviations of the means of HVL ratios for beam quality estimations were less than 5% difference. The means and standard deviations used to evaluate the accuracy of SpekCalc and IPEM78 models in estimating the HVL values for both Phil and GE x-ray machines are summarized in Table 3. The mean HVL ratio for SpekCalc model was calculated by using the HVL ratios of both fine and broad focuses estimated using SpekCalc for both machines. The same method was used to determine the mean HVL ratio for IPEM model. The HVL ratios then used to calculate the standard deviation for each model. Both the SpekCalc and IPEM78 models had shown the percentage difference of mean and standard deviation within 5% for the means of HVL ratios estimated for both Phil and GE x-ray machines.

Discussion

There is a maximum of 5.07% difference of the effective energies between the fine focus and broad focus for both Phil and GE x-ray machines. Most of the effective energies of broad focus were slightly lower than that of fine focus for both x-ray machines. The effective energies of Phil x-ray machine were higher than GE x-ray machine because of the thicker filtration in aluminium equivalent inside its x-ray tube.

SpekCalc mostly underestimated the beam quality for both Phil and GE x-ray machines especially at higher tube voltages except at lower tube voltages for broad focus on both Ge and Phil x-ray machines. Similar finding was obtained by Poludniowski et al. (7). SpekCalc showed an agreement within 5% to the measurement in estimating the beam quality. Whereas IPEM78 overestimated the beam quality for both x-ray machines and at all tube voltages except 60 kVp and 70 kVp for fine focus of the Phil x-ray machine. Similarly, IPEM78 showed an overestimation of the beam quality from tube voltages 50 kVp to 250 kVp (7). The IPEM78 estimated the beam quality higher than the measured beam quality as reported by Ay et al. (5). However, in this study, IPEM78 showed an agreement within 5% to the measurement in estimating the beam quality except at 81 kVp for the broad focus of the GE x-ray machine and at 50 kVp for both broad and fine focuses of the Phil x-ray machine.

The total filtration of the x-ray machine is required as an input parameter for all the computational models. The determination of total filtration is important because its value will influence the theoretical results. In this study, the total filtration of Phil x-ray machine was obtained from the manual of the machine and the total filtration for GE x-ray machine was obtained from the label on the x-ray tube. The filtrations were not the actual thickness and materials of the filter inside the tube but the thickness in aluminium equivalent. Therefore, without well-known of the actual filtration inside the x-ray tube, the thickness in aluminium equivalent of the inherent filtration was used as the input parameter for SpekCalc and IPEM78 models. This could affect the beam quality estimation by using these softwares. However, for the diagnostic range x-ray machine with focus to detector distance (FDD) 104 cm, the total filtration in millimeter aluminium (mm Al) of the x-ray tube from tube voltages 50 kVp to 125 kVp does not vary much except for 50 kVp (9).

SpekCalc showed the percentage difference of mean is 1% underestimation with the percentage difference of standard deviation is 3% while IPEM78 showed the percentage difference of mean is 4% overestimation with the percentage difference of standard deviation is 2% compared to the measured beam quality. Overall, both the SpekCalc and IPEM78 models had shown that both the means and standard deviations were within 5% respectively for beam quality estimations for both Phil and GE x-ray machines. These two models are
reliable to be used as computational models to predict the HVLs that used to characterize the beam quality of x-ray spectra generated with different tube voltages in clinical environment.

The limitation of this study is the difficulty in determining the actual total filtration of the x-ray tube for both Phil and GE machines. The total filtration for both of the x-ray tubes was given in millimetre aluminium equivalent (mm Al). The total filtration of a machine must be determined because it is required as an input parameter for SpekCalc and IPEM78. Its value will influence the predicted result. Without well-known of the actual filtration inside the x-ray tube, the beam quality estimation with the SpekCalc and IPEM78 models will be influenced. For the future study, there must be a proper way to determine the actual total filtration of the x-ray machine studied.

Conclusion

Both SpekCalc and IPEM78 showed means and standard deviation differences within 5% in the determination of HVLs over Phil and GE machines. However, SpekCalc showed better agreement with the measured HVLs compared to IPEM78. The successful use of SpekCalc and IPEM78 in HVL estimation used for x-ray beam quality instant prediction is depended on the accuracy in determining the actual total filtration in the x-ray machine. The actual total filtration of the x-ray machine must be determined and used for future study for better accuracy in HVL prediction.

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Authors’ Contributions

Conception and design, drafting of the article: CSC
Collection, assembly, analysis, and interpretation of the data: JWL
Critical revision of the article, administrative, technical, or logistic support: AZH

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References


**Figure 1:** SpekCalc Graphical User Interface (GUI).

**Figure 2:** IPEM78 Graphical User Interface (GUI).
Figure 3: The experimental setup for HVL measurement.

Figure 4: Transmission curves of the x-ray beam for tube voltages 50 kVp to 125 kVp of Phil x-ray machine with (a) fine focus and (b) broad focus. The solid lines showed the measured data and the dashed lines showed the best fit line for HVL determination (in cm Al).
**Figure 5:** Transmission curves of the x-ray beam for tube voltages 50 kVp to 125 kVp of GE x-ray machine with (a) fine focus and (b) broad focus. The solid lines showed the measured data and the dashed lines showed the best fit line for HVL determination (in cm Al).

**Figure 6:** Energy of x-ray beam versus linear attenuation coefficient, $\mu$ for effective energy determination based on NIST data. The solid line showed the data from the NIST and the dashed line showed the best fit line for determination of the effective energy.
Table 1: Comparison of effective energy for Phil and GE x-ray machines for tube voltages in the diagnostic radiology energy range

<table>
<thead>
<tr>
<th>Tube Voltage, kVP</th>
<th>Philips X-ray Machine</th>
<th>GE X-ray Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effective Energy, keV</td>
<td>Effective Energy, keV</td>
</tr>
<tr>
<td></td>
<td>Fine Focus</td>
<td>Broad Focus</td>
</tr>
<tr>
<td>50</td>
<td>30.49</td>
<td>30.49</td>
</tr>
<tr>
<td>60</td>
<td>34.87</td>
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<tr>
<td>70</td>
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<tr>
<td>102</td>
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<td>42.24</td>
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<tr>
<td>109</td>
<td>43.70</td>
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</tr>
<tr>
<td>125</td>
<td>45.83</td>
<td>45.88</td>
</tr>
</tbody>
</table>

*The deviations were related to the fine focus.
Table 2: Comparison between HVL estimations of SpekCalc and IPEM78 models to measurements for tube voltages in the diagnostic radiology energy range for Phil and GE x-ray machines

<table>
<thead>
<tr>
<th>Tube Voltage (kVp)</th>
<th>Philips x-ray Machine</th>
<th>GE x-ray Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HVL Ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine Focus</td>
<td>Broad Focus</td>
</tr>
<tr>
<td></td>
<td>SpekCalc Measurement</td>
<td>SpekCalc Measurement</td>
</tr>
<tr>
<td>50</td>
<td>1.10</td>
<td>1.09</td>
</tr>
<tr>
<td>60</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>70</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>81</td>
<td>0.97</td>
<td>1.00</td>
</tr>
<tr>
<td>90</td>
<td>0.96</td>
<td>1.00</td>
</tr>
<tr>
<td>102</td>
<td>0.98</td>
<td>1.02</td>
</tr>
<tr>
<td>109</td>
<td>0.96</td>
<td>1.01</td>
</tr>
<tr>
<td>125</td>
<td>0.97</td>
<td>1.02</td>
</tr>
<tr>
<td>Mean</td>
<td>0.98</td>
<td>1.01</td>
</tr>
<tr>
<td>SD*</td>
<td>0.048</td>
<td>0.040</td>
</tr>
</tbody>
</table>

*SD is the standard deviation.

Table 3: Comparison between SpekCalc and IPEM78 models in HVL estimation for both Phil and GE machines

<table>
<thead>
<tr>
<th>Computational Models</th>
<th>Mean HVL Ratio</th>
<th>Standard Deviation</th>
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</thead>
<tbody>
<tr>
<td>SpekCalc</td>
<td>0.99</td>
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<tr>
<td>IPEM78</td>
<td>1.04</td>
<td>0.02</td>
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