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Correlation between X-ray tube current exposure time and X-ray photon number in GATE

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Abstract

Background: The image quality of X-ray imaging relies heavily on the emitted X-ray photon number which is dependent on the X-ray tube current and the exposure time. A limiting factor of good image quality is the radiation dose that will be delivered to the object. To accurately estimate the absorbed dose in an imaging protocol, it is better to simulate the X-ray imaging with a Monte Carlo platform such as GATE (Geant4 Application for Tomographic Emission). However, the input of GATE is the X-ray photon number of the simulated X-ray tube. So far, there is no good way to setup the photon number for a desired X-ray tube current setting.

Objective: To provide a method to correlate the experimental X-ray tube current exposure time and the X-ray photon number in GATE.

Methods: The accumulated radiation dose of a micro-computed tomography (CT) X-ray tube at different current exposure times was recorded with a general-purpose ion chamber. GATE was used to model the experimental microCT imaging system and record the total absorbed dose (cGy) in the sensitive volume of the ion chamber with different X-ray photon numbers. Linear regression models are used to establish a correlation between the estimated X-ray photon number and the X-ray tube settings. At first, one model establishes the relationship between the experimentally measured dose and the X-ray tube setting. Then, another model establishes a relationship between the simulated dose and the X-ray number in GATE. At last, by correlating these two models, a regression model to estimate the X-ray output number from an experimental X-ray tube setting (milliampere-seconds (mAs)) is obtained.

Results: For a typical micro-CT scan, the X-ray tube is operated at 50 kVp and 0.5 mA for a 500 ms exposure time per projection (0.25 mAs). For these X-ray imaging parameters, the X-ray number per projection is estimated to be 3.918×10^6 with 1.0 mm Al filter.

Conclusion: The findings of this work provide an approach to correlate the experimental X-ray tube current exposure time (mAs) to the X-ray photon number in the GATE simulation of the X-ray tube to more accurately determine the radiation dose for an imaging protocol.

Keywords: X-ray imaging, GATE, Monte Carlo

1. Introduction

X-ray imaging has remained as the workhorse of medical imaging due to its fast acquisition speeds and high spatial resolution [1]. The intensity of the X-rays is dependent on the X-ray tube current and exposure time. Hybrid X-ray imaging modalities like X-ray luminescence computed tomography (XLCT) and X-ray fluorescence computed tomography (XFCT) rely on the intensity of the X-ray tube to provide an accurate and time efficient image of the nanoprobes in the imaged objects [2-4]. XLCT and XFCT can use X-ray excitable exogenous contrast agents to monitor drug delivery and track the progression of diseases like cancer [5-10]. However, the dose absorbed by the imaged sample from X-ray photons is a concern and therefore it limits the image quality and applications [1, 11]. There are ways to measure the X-ray dose experimentally, but current methods are limited and/or standardized to a specific imaging object size and imaging protocol [12-14]. These methods also often include instruments that suffer from oversaturation, pile up effects, energy dependence, temperature dependence, and/or dose rate dependence which reduce the accuracy of the measurements [15-17]. Therefore, it is better to numerically simulate the X-ray imaging to accurately calculate the absorbed dose.

Among the Monte Carlo software available for medical imaging applications, the Monte Carlo software, GATE (Geant4 Application for Tomographic Emission) has gained attentions in medical imaging applications [18-21]. GATE is an open-source software which was developed by the international OpenGATE collaboration as a GEANT4 wrapper that encapsulates the GEANT4 libraries specific to medical imaging and radiotherapy [22]. GATE utilizes the macro language to ease the learning curve of GEANT4 and allow GEANT4 toolkits to be more accessible to medical imaging and radiotherapy researchers [20, 22]. GATE has now allowed for the design and optimization of new medical imaging devices and radiotherapy protocols [21]. However, to model the X-ray imaging system in GATE the X-ray number is needed. The X-ray number in the Monte Carlo GATE software is the number of X-ray photons which will be initialized for the imaging simulation. This X-ray photon number is defined by the user. However, in an experimental imaging protocol, it is the tube current exposure time to be recorded (mAs). One cannot use the tube current exposure time as the input in GATE to simulate the X-ray imaging or dose. Therefore, to model an experimental imaging protocol with an X-ray tub setting in mAs, a method to correlate the X-ray photon number in GATE to the experimental X-ray tub setting in mAs should be explored. So far, to the best of our knowledge, there is no good way to model the X-ray tube's output of X-ray photon number in GATE for a given X-ray tube current.

In this work, the X-ray output number from a cone beam micro computed tomography (micro-CT) X-ray tube is estimated using Monte Carlo GATE. An ion chamber is used to record the accumulated exposure in Roentgens (R) of the X-ray tube for various exposure times. The exposure measurements were then converted to dose in air. The X-ray tube spectrum and measurement setup were modeled in GATE to generate a linear relationship between the radiation dose in the modeled ion chamber and the X-ray photon number. The measurement data and the trendline equations from the GATE simulations were then used to determine the X-ray output number from the dose in the experimental setup for each exposure time. Several aluminum filter thicknesses were incorporated in the experimental imaging protocol to explore the effects of filtration on X-ray output.

The paper is organized as follows. In section 2, the methods of the GATE simulations, experimental setup for source spectra measurements and dose exposure are presented. In section 3, the results showing the relationships between X-ray output and dose with different spectra are presented. The paper concludes with discussions of the results and future works.

2. Methods

2.1 Experimental setup for X-ray source spectra measurement

The spectrum of an Oxford Instruments X-ray tube (Oxford XTF5011) was acquired using an Amptek CdTe 123 spectrometer. The X-ray tube has a cone angle of 23 degrees and was operated at 50 kVp and 1 μA. To avoid oversaturation and pile up effects, a 2 mm thick, 2 mm diameter pinhole collimator was inserted in the front of the spectrometer sensor. The spectrum was acquired for 60 seconds. The spectra of the X-ray tube with Aluminum (Al) filters of thickness 0.0, 0.5 mm, and 1.0 mm were collected.

2.2 Experimental setup for X-ray Exposure Measurement

The X-ray exposure was measured using an Accu-Dose system (Radcal, Monrovia, CA) with a general purpose in-beam ion chamber (10X6-6, Radcal). The Accu-Dose system meter allows for at most 4 digits when making a measurement. The ion chamber head has a diameter of 25 mm and a length of 38 mm. The active component of the ion chamber head has a volume of 6 mm^3. The ion chamber was positioned 17.78 cm away from the X-ray tube window, which is the isocenter of the micro-CT setup. The X-ray tube was operated at 50 kVp and 0.5 mA. The X-ray tube system and the ion chamber were positioned inside a lead cabinet. The Accu-Dose system was placed outside the lead cabinet. The ion chamber cable was fed through a lead cabinet hole to be connected to the Accu-Dose system. The setup of the exposure acquisition and the Accu-Dose system is seen in Fig. 1. The exposure was acquired in Roentgen units (R) for different exposure times: 1, 2, 4, 8, 10, and 20 seconds which correspond to tube current exposure times: 0.5, 1, 2, 4, 5, 10 mAs.

Each exposure reading was repeated six times for each exposure time to reduce the variance from the Accu-Dose system measurements. The average exposure was taken from the measurements for each exposure time. The Accu-Dose system measurements account for corrections factors due to temperature and pressure values which may be different from standard temperature and pressure in air. The Dose-to-air in the sensitive volume was found directly from the mean exposure by using the roentgen-to-cGy conversion factor, 0.876 cGy/R [11, 13, 17].

2.3 GATE simulation setup

A schematic and snapshot of the GATE simulation is seen in Fig. 2. The ion chamber was modeled as a cylinder with wall material composed of polycarbonate. The sensitive volume of the ion chamber was also modeled as a cylinder of air with 6 cm^3 volume positioned at the center of the ion chamber head. The X-ray tube spectra were imported into GATE using the user spectrum function which by a fixed default normalizes the imported spectra. The GATE simulations employed the GEANT4 emstandard_opt4 physics builder to model the physical processes [20]. In the GATE simulation, the radiation dose can be stored in a 3D matrix using the "DoseActor" tool [23]. The mass weighting algorithm was employed for the dose calculations, in which the dose was calculated as the energy deposited per unit mass of the voxel within the dose matrix. The dose matrix was discretized into 25 x 25 x 40 voxels of 1 mm^3 size. 10^6, 2 x 10^6, 10^7, and 2 x 10^7 X-rays were initialized in GATE to create a linear trendline model between the X-ray number and the radiation dose for each Al filter thickness. The absorbed dose in the modeled ion chamber sensitive volume was masked to only identify the voxels found within the sensitive volume. The dose voxels were then summed to acquire the total absorbed dose in the sensitive volume. The tube X-ray photon number for each measured dose was determined from a trendline model equation.

All dose calculations from the modeled ion chamber sensitive volume were performed in MATLAB.

Aside from measuring the accumulated exposure, the Accu-Dose system also allows for the measurement of the exposure rate (R/min). The exposure rate was measured to validate the accuracy of the linear model equations for each Al filter thickness. The exposure rates (slopes) of the linear model equations are compared with the measured exposure rates after conversion from R/mAs to R/min.

2.4 X-ray tube output model generation

Linear regression models are used to establish a relationship between the estimated X-ray photon number and the experimental X-ray tube setting. The first regression model establishes a relationship between the experimentally measured X-ray radiation dose and the X-ray tube setting. This model is obtained from fitting experimental measurements acquired with the Accu-Dose system. The second regression model is obtained by fitting the simulated the X-ray radiation dose and the known X-ray photon number in GATE using the captured X-ray tube spectra. By correlating both models, a regression model which estimates the X-ray photon number from the experimental X-ray tube setting is obtained and can be used as an input for GATE simulation for the specific X-ray tube setting.

3. Results

3.1 X-ray tube spectra

The acquired spectra for each Al filter case are plotted in Fig. 3. The L-shell energies of the tungsten anode target are clearly visible in Fig. 3a when no Al filter is used. With 0.5 mm Al thickness, the L-shell energies are effectively attenuated, and their intensity reduced as seen in Fig

3b. With 1 mm Al thickness, the L-shell energies are essentially nonexistent as seen in Fig. 3c. The energies below the bremsstrahlung curve are from Compton scattering effects caused by the Al filter or spectrometer collimator.

3.2 Measured X-ray Radiation Dose

Fig. 4 shows the linear regression plots formed from the mean of the exposure measurements (in Roentgens, R) with the ion chamber for each exposure time (milliampere-seconds, mAs) of the Oxford X-ray tube. All regression plots showed a high positive linearity with all R^2 values being greater than 0.99.

The highest exposure rate was seen without the Al filter due to the absorption of the L-shell energies from the tungsten anode. The plots of the 0.5 mm Al, and 1.0 mm Al are more similar since the L-shell energies have significantly been removed. The lowest exposure rate is seen with 1.0 mm Al filter thickness.

Table 1 compares and validates the accuracy of the linear trendlines equations displayed in Fig. 4. The exposure rates (slopes) of the linear model equations are compared with the measured exposure rates after conversion from R/mAs to R/min. Table 1 shows the percent error (PE) between the measured exposure rate and the modeled exposure rate for each Al filter thickness. The modeled exposure rates are obtained from the trendline equations in Fig. 4. All modeled exposure rates are accurate within 5% of the measured exposure rate. The highest percent error was seen with 1.0 mm Al filter while the lowest percent error was seen with 0.5 Al filter thickness.

3.3 The Radiation Dose Calculated by GATE

Fig. 5 shows the linear regression plots relating the X-ray number and the total absorbed dose in cGy for each Al filter thickness. The largest rate is observed with 0.5 mm Al filter thickness, and the lowest rate is observed with 1.0 mm Al filter thickness. A larger number of X-ray photons is required with the 1.0 mm Al filter to achieve a similar dose as the other Al filter thickness. All regression plots showed a high positive linearity with all R^2 values being greater than 0.99. The trendlines equations are used to convert the experimental dose readings into the X-ray output number in GATE for a given current exposure time (mAs).

3.4 Correlation between the Photon Number in GATE and the X-ray Tube Current

Fig. 6 shows the plots relating the X-ray number and the exposure time in milliampere-seconds (mAs) for the Oxford X-ray tube. The largest output rate is observed without the Al filter and the lowest output rate is observed with 1.0 mm Al filter thickness. All regression plots showed a high positive linearity with all R^2 values being greater than 0.999.

For a typical micro-CT scan, the X-ray tube is operated at 50 kVp and 0.5 mA for a 500 ms exposure time per projection (0.25 mAs). It is standard for a tungsten anode X-ray tube to have a 1.0 mm Al filter to remove the anode L-shell emissions. From Fig. 6, the X-ray output number per projection can be estimated through linear extrapolation. The X-ray number per projection is estimated to be 3.918×10^6 with 1.0 mm Al filter.

4. Discussion

The accuracy of the X-ray output estimate in this work depends heavily on the specifications of the imaging system and dose measurement system. Parameters like the beam cone angle, distance between the source and ion chamber, the size of the sensitive volume inside the ion chamber head, and ion chamber wall material are important to include in the GATE simulation. Another limiting factor is the normalization of the spectrum that GATE performs as a default operation which is hardcoded in the software. The normalized spectrum becomes a probability distribution of energies from which GATE selects randomly when an X-ray is initialized. A high number of X-rays needs to be initialized to generate X-rays with an energy distribution like the original spectrum.

The increased exposure rate with decreased Al filter thickness is due to the reduced average beam energy with lower filter thickness. From Fig. 3, it can be observed that the average X-ray energy increases with greater Al filter thickness since the filter removes the L-shell energies of the tungsten anode seen in Fig. 3a. The physical process responsible for a large contribution of the dose is the photoelectric effect which is inversely proportional to the X-ray energy. Therefore, the highest dose rate is observed without the Al filter.

The curves of Fig. 4 are more different compared to the curves of Fig. 5 which are more similar. Note that Fig. 4 shows the relationship between the experimentally measured exposure and the X-ray tube mAs setting while Fig. 5 shows the relationship between the absorbed dose and the X-ray photon number simulated in GATE. In Fig. 4, the curve without an Al filter is much greater than the other curves since more X-rays are being emitted for the tube current exposure time (mAs) setting. The X-ray spectrum associated with this curve is 3a. This spectrum shows the L-shell energy emission of the tungsten anode of the X-ray tube. L-shell energies are very bright (intense) due to their high interaction cross section. The L-shell energies are attenuated and removed as the Al thickness is increased. Therefore, the intensities of the other spectra (3b,3c) are not as great as in Figure 3a. The similarity in the curves of Fig. 5 is due to the X-ray number being the same for all Al thickness spectra and so the intensity of each spectrum is the same unlike Fig. 4 which results in little variation of the dose.

In Fig. 5, the highest dose rate is observed with the 0.5 mm Al filter. This may be due to the greater effective energy with 0.5 mm Al which allows for the X-rays to become more penetrative. This leads to more dose onto the sensitive volume of the modeled ion chamber after the X-rays have traversed the ion chamber wall. However, little difference in the dose rates is observed when the 0 mm Al filter or 0.5 Al filter is used compared with the 1 mm Al filter. Without an Al filter, some of the L-shell energies of the target anode can pass the chamber wall and deposit their energy onto the sensitive volume of the ion chamber since the L-shell energies are most intense without the Al filter.

Fig. 6 is the final model result which gives an estimation of the X-ray tube photon number for an X-ray tube current exposure time setting. Fig. 6 is our final goal of this study, from which one can find the X-ray photon number as input in GATE for any experimental X-ray tube settings (mAs). By having a better estimation of the X-ray tube output, the radiation dose for an imaging protocol can be accurately estimated without using standardized methods.

The ion chamber was positioned at the iso-center since that is the position of the imaged object and the ion chamber is fully covered by the X-ray tube cone beam. In this work, the X-ray photon number in the X-ray beam after filtering is correlated with the X-ray tube current. To correlate the photon number before filtering including the factor of X-ray self-attenuation, more detailed information of the X-ray tube product is required. However, intellectual property right is an obstacle to circumvent.

The trendline coefficient of determinations between X-ray number and absorbed dose is consistent with previous work and literature in which a strong linear relationship with a high coefficient of determination, $R^2 >= 0.97$ between the X-ray number and the radiation dose exists [11, 24]. The trendline equations and X-ray photon numbers in this work are within standard small animal X-ray imaging parameters [25].

This work can be applicable to any X-ray tube that uses the cone or fan beam geometry if the sensitive volume of the ion chamber can be completely covered by the X-ray beam or if good partial volume response can be achieved with the ion chamber. For smaller X-ray beams, like pencil beams, film dosimetry or diode edge detectors need to be integrated into the presented method.

5. Conclusion

In this work, the X-ray tube output of a small animal micro-CT imaging system was estimated using Monte Carlo GATE. Exposure measurements were performed on the imaging system using an ion chamber. By comparing the simulated dose in GATE with the measured dose in the experimental setup, the X-ray photon number is found to be linearly correlated with the X-ray tube current exposure time in mAs. The linear correlation is changed with different X-ray filters. From the linear correlation, it is straightforward to setup the X-ray photon number in the GATE simulations according to the desired exposure time. The proposed method offers a simple solution to measure the X-ray photon number from an X-ray tube for any imaging design/X-ray tube setting. From the X-ray output estimate, Monte Carlo software like GATE can be used to measure the radiation dose delivered to the imaging object which is more accurate than standardized methods. In the future work, X-ray photon number estimation methods will be explored in pencil beam based X-ray imaging system.

Acknowledgments

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FIGURES

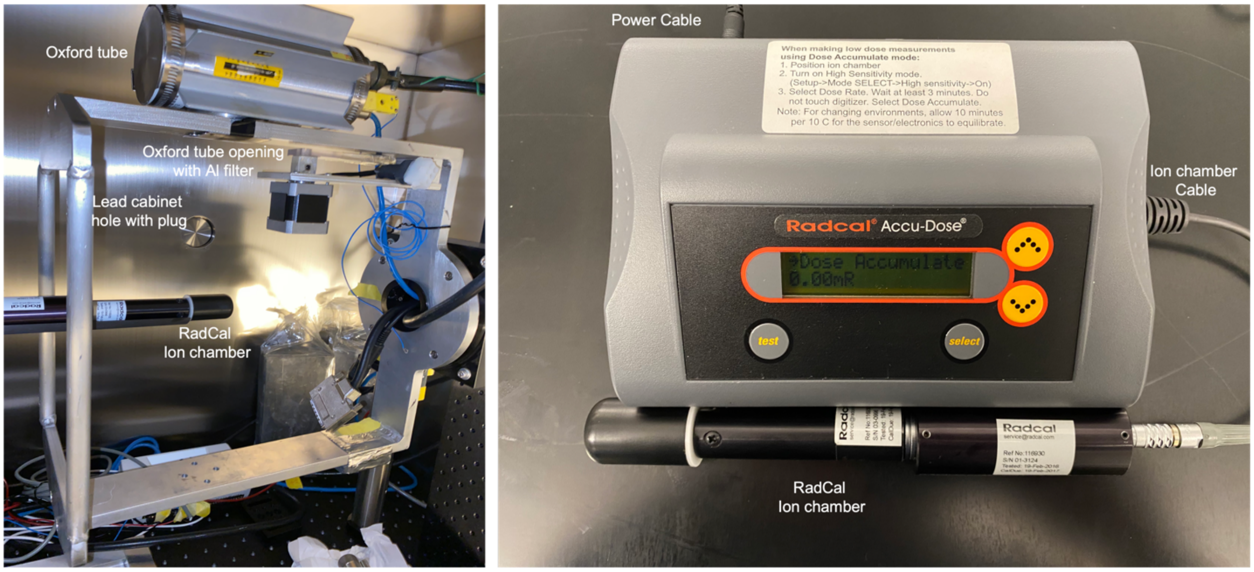

Fig. 1: Experimental acquisition setup (left) and the Accu-Dose system (right). The Accu-Dose system was positioned outside of the lead cabinet for user control.

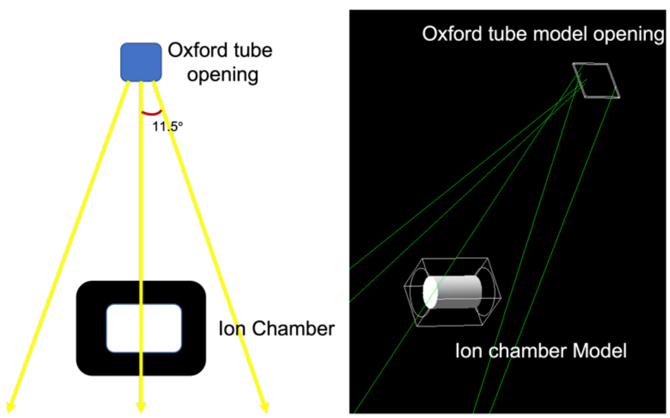

Fig. 2: Schematic (left) and snapshot (right) of the GATE simulation for the dose acquisition. The green lines in the snapshot are the X-ray beams. The sensitive volume of the ion chamber is modeled as the white cylinder.

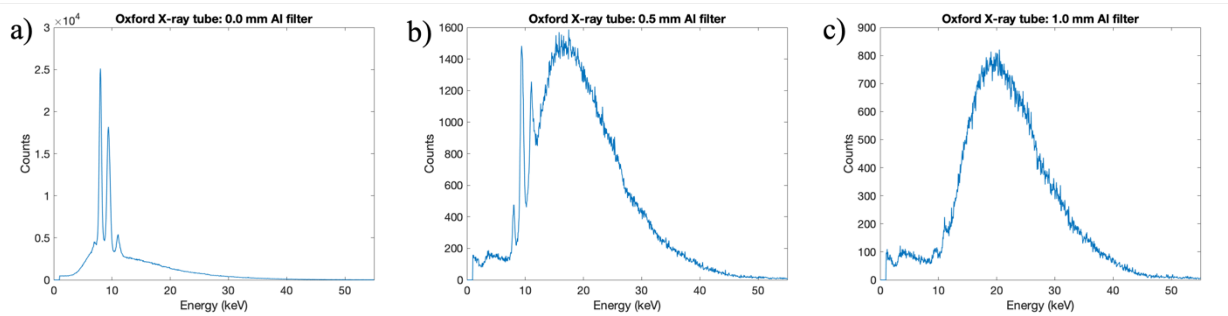

Fig. 3: Spectrum of the Oxford X-ray tube with different Al thickness: a) 0.0 mm, b) 0.5 mm, c) 1.0 mm.

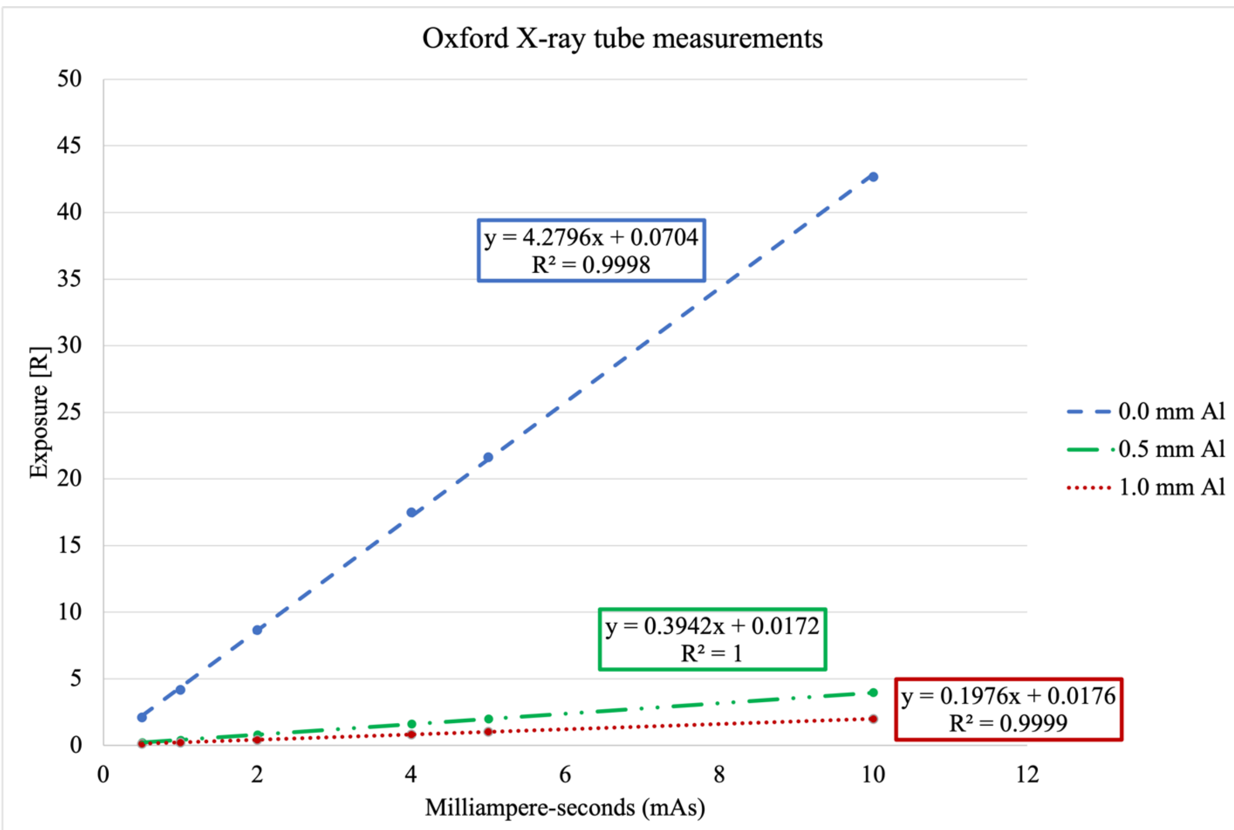

Fig. 4: Linear regression plots between the mean X-ray radiation dose (R) and the tube current exposure time (mAs). This plot was generated from the tube exposure measurements.

Table 1: Comparison of the modeled exposure rate to the measured exposure rate at 0.5 mA tube current for each Al filter thickness.

Al filter thickness (mm)	Measured Exposure Rate (R/min)	Modeled Exposure Rate (R/min)	Percent Error (%)
0.0	133.6	128.4	4.050
0.5	11.85	11.83	0.1691
1.0	5.641	5.928	4.841

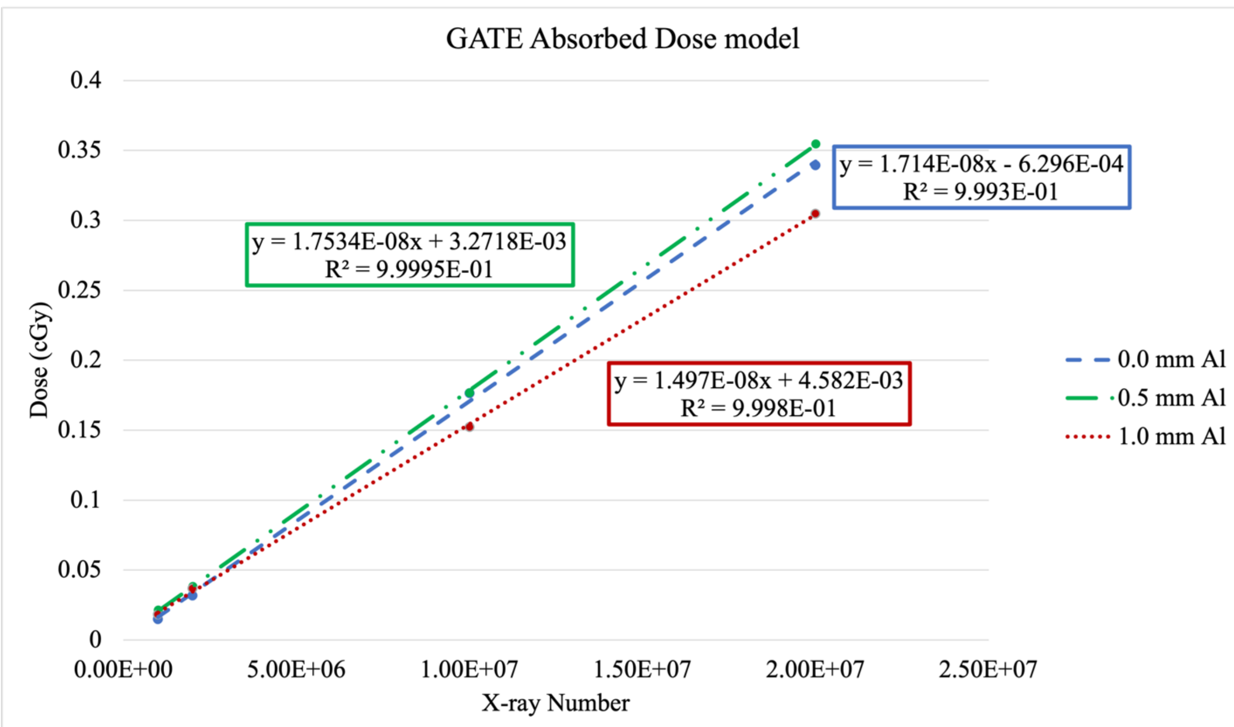

Fig. 5: Linear regression plots between the X-ray photon number and total absorbed dose (cGy) modeled in GATE.

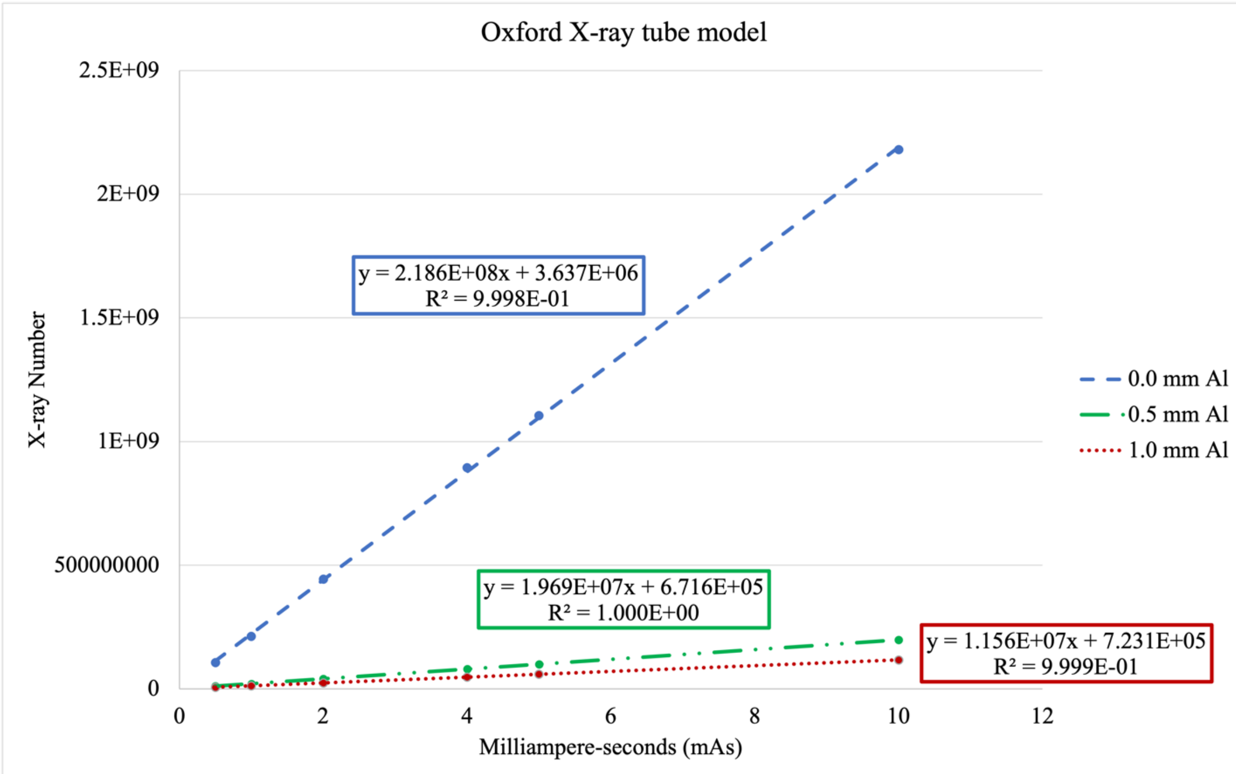

Fig. 6: Linear regression plots between the X-ray photon number and the exposure time (mAs).