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DOSIMETRY TESTING FOR A NEW IN VIVO X-RAY FLUORESCENCE MEASUREMENT SYSTEM

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Abstract

Lead exposure poses severe health risks to individuals, impacting cognitive function, growth, learning, and behavior. Current lead detection methods, primarily blood testing and X-ray fluorescence (XRF) of bone, both have limitations. This study introduces a novel in vivo XRF measurement system using K-shell energies of lead, addressing limitations of previous methods. The study aimed to characterize beam directionality, subject radiation dose, and operator occupational exposure.

Using a high-energy x-ray tube and room-temperature detectors, various parameters were assessed with bone and tissue phantoms. Dose measurements were taken by altering voltage, current, and shielding. Scatter and spatial measurements highlighted increased scatter with bone and tissue presence, emphasizing the safest positions for bystanders and operators.

Results exhibited expected dose rate changes with varying parameters, showcasing the impact of bone and tissue on scatter radiation. The system's total body effective dose for an adult was 1.94 μSv and a child aged 10 years was 3.28 μSv with an 8 mm molybdenum shielding indicating minimal risk compared to established public dose limits.

This system demonstrates promising capabilities for lead exposure monitoring, offering negligible occupational exposure and minimal risk to individuals being scanned. Its safety and efficacy position it as a valuable tool in assessing lead exposure, potentially improving preventive measures.

Keywords

dose assessment; exposure; radiation; x-rays; metal; trace

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INTRODUCTION

Lead is a hazardous element that has detrimental effects on the human body (Lin et al. 2019). Its impact extends to the brain and nervous system, resulting in impairments such as compromised cognitive function, hindered growth and development, challenges in learning and behavior, as well as issues related to hearing and speech (USATSDR 2007). There are two prevailing methods to detect lead following an exposure, blood testing and x-ray fluorescence (XRF) of the bone; however, both methods have their limitations (Rabinowitz 1991; Hu et al. 2007). The short half-life of lead in blood makes blood testing only useful for measuring recent lead exposures (Hu et al. 2007; Specht et al. 2016, 2018b). Bone proves to be a better biomarker of exposure for cumulative, chronic exposures to lead – more than 90% of ingested lead deposits in the bone, which is associated with elevated brain lead levels (Hu et al. 2007; Specht et al. 2018b, 2019b).

The current method of bone lead measurements uses XRF (Specht et al. 2014, 2018a). However, the current methods have limitations. The standard portable XRF method, which uses L-shell fluorescence, has limitations in the measurement of trabecular bone, which was previously shown to have different accumulation kinetics to cortical bone and relate slightly more effectively to certain health outcomes (Weisskopf et al. 2007; Specht et al. 2019a, 2023; Zhang et al. 2021). In addition, the portable XRF can have limitations based on skin thickness, but current iterations of the method have reduced the uncertainty from added tissue significantly (Zhang et al. 2021). The current K-shell XRF instrument uses a radioisotope source that was more complicated to license and transport; had a 30-minute measurement time; and used liquid nitrogen cooled equipment (Chettle et al. 1991). It would be highly beneficial to use a single system capable of measuring both the cortical and trabecular bone, rather than just cortical bone, as done previously using the K-shell of lead, but without many of the disadvantages of the previous system.

To overcome these challenges in lead monitoring, we developed a novel method that utilizes K-shell energies from lead in tandem with an x-ray tube source as opposed to the traditionally used radioisotope (Specht et al. 2016). Also, our new system uses two room-temperature operable detectors whereas past K-shell XRF methods utilized bulky, liquid nitrogen-cooled Germanium detectors (Gordon et al. 1993; Specht et al. 2016). Our studies indicate that a new detector based on an x-ray tube setup would be viable for measurement with detection limits on par with conventional KXRF bone lead measurement systems (between 6–10 $\mu\text{g g}^{-1}$) (Specht et al. 2017). Previous cloverleaf KXRF systems have detection limits better than this at approximately 2–3 $\mu\text{g g}^{-1}$ and portable XRF systems utilizing the L-shell typically have detection limits in approximately this same range, but do not have the ability to measure trabecular bone (Johnson et al. 2020; Zhang et al. 2021). L-shell lead measurements utilize an x-ray beam of average energy between ~20–30 keV, thus have penetration limits within bone of approximately 0.5 mm, which previous studies have indicated make it impossible to penetrate into actual trabecular bone (Specht et al. 2019a, 2023). However, K-shell XRF for lead in bone was used widely in the 90's and early 2000's for measurement of bone trabecular and cortical bone sites (Weisskopf et al. 2007; Zheutlin et al. 2018). It would represent a major advantage to have a system capable of measuring trabecular bone, operable at room temperature, and using an x-ray tube source.

Our goals in this study were to characterize the beam directionality, radiation dose to subject, and occupational dose for operators of the system. With intentions to deploy the system in settings that offer little shielding, an effective assessment of the beam is necessary to determine exposure to those being measured, bystanders, and operators. By varying current, voltage, and filtration with bone and tissue phantoms, we measured the resulting effect on the delivered dose to these individuals.

METHODS AND MATERIALS

Measurement System Setup

The new system uses a 140G Moxtex high energy x-ray tube and two Amptex CdTe room temperature detectors. The x-ray tube is set to 140 kV and 20 μ A at a 90-degree geometry for the detectors and is designed to measure lead in the tibia. During the system's development, two different shields were designed to be used with the x-ray tube to experimentally determine which would allow for the best detection. The shields are 8 mm and 10 mm thick; both are made of molybdenum and feature a 1 mm diameter, 4 mm deep cylindrical hole to collimate the beam. With the 8mm shield attached, we produced a spectrum, like that seen in Fig.1, of the x-ray energies. If lead is present in the bone, we expect to see a corresponding spike at approximately 88 keV.

For use in a clinical setting, this XRF detection system is paired with an aluminum constructed frame shown in Fig. 2. The frame features adjustable housing for both the 140 KV x-ray tube and the two CdTe detectors, with movement applicable in vertical and horizontal planes to best orientate for any given subject. Furthermore, the moveability of housing allows for the system to be deployed in a variety of settings. With an open 90-degree portion of the frame, a subject can simply step into the apparatus, adjust housings to proper position, and lead detection can begin.

Dosimetry Measurements

Dose measurements were performed using a RadEye B20 survey meter with the 10 mm deep dose filter. The filter was chosen because of the flat response rate provided across a wide range of energies (Thermo Fisher Scientific 2017). This allowed us to take a myriad of real time measurements to determine the spatial properties of dose effectively. Measurements were taken holding voltage constant at 140 kV and adjusting current between 3 and 20 μ A to assess the variation with current. Conversely, additional measurements were taken holding current constant at 20 μ A and adjusting voltage between 90 and 140 kV.

Soft tissue and bone equivalent phantoms were used to better ascertain how scanning a real calf would affect the dose rate to bystanders. Lucite phantom plates were used to simulate soft tissue. A plaster-of-Paris bone phantom doped with 20 ppm lead was used to assess an individual who had been exposed to lead. Measurements were taken with no bone or tissue phantoms (Fig. 3a), with just the bone phantom (Fig. 3b), and with the bone and tissue phantom (Fig. 3c) to assess induced scatter in each of these scenarios.

Measurements were taken to determine dose rate in the area, scatter, and spatial measurements. Scatter measurements were taken 5, 15, 30, 45, and 60 cm from the source

at 0, 45, 90, 135, and 180 degrees from the beam. Spatial measurements were taken at varying height and widths from the source. These measurements were taken in line with, at 2 feet (0.61 m) from, and at 4 feet (1.22 m) from the source, totaling to 225 measurements encompassing spatial scatter and beam measurements.

For total effective dose calculation, we first experimentally determined the effective linear attenuation coefficient. This was done by taking measurements with the 8mm molybdenum shield and 10mm molybdenum shield at 15, 30, 45, and 60 cm from the x-ray tube. The effective linear attenuation coefficient was calculated at each distance and the average was taken. This average was then used to calculate a total effective dose for both a child and adult at varying shielding thicknesses based on measurements taken.

RESULTS

Figs. 4 and 5 show the resulting dose rate from changing current and voltage, respectively. Fig. 4 shows a linear relationship between dose rate and current while holding voltage constant at 140 kV. Fig. 5 shows a significant non-linear relationship between dose rate and voltage while holding current constant at 20 μA .

Figs. 6a–d show the dose rate at 5, 15, 30, and 45 cm from the source, respectively. Each graph shows the dose rate 45, 90, and 135 degrees from the source. Furthermore, at each degree the dose rates with no bone or tissue, with just bone, and with bone and tissue are shown. Measurements 60 cm from the beam at all degrees showed a dose rate less than 1 $\mu\text{Sv hr}^{-1}$ and measurements 180 degrees from the beam had a dose rate equivalent to background readings (0.11 $\mu\text{Sv hr}^{-1}$). These dose rates were deemed insignificant and excluded from the figures.

Figs. 7a–c depict dose rates taken 0, 2, and 4 feet (0, 0.61, and 1.22 m) from the x-ray tube, respectively. At each distance from the source, measurements were taken without bone or tissue phantoms, with only bone, and with bone and tissue phantoms present. Along the vertical axis, measurements were taken 0.5 feet (0.15 m) from the floor, 2 feet (0.61 m) from the floor, in line with the tube (TUBE), 4.5 feet (1.37 m) from the floor, and 6 feet (1.83 m) from the floor. Along the horizontal axis, measurements were taken in line with the tube, and 1.5 and 3 feet (0.46 and 0.91 m) to the left and right of the tube.

Table 1 shows measurements taken 15, 30, 45, and 60 cm from the source directly in line with the beam with an alternated 10 mm and 8 mm shield. The effective linear attenuation coefficient was then calculated for each distance and the average was then taken from each measured distance. We thus determined that the effective linear attenuation coefficient for this setup is 0.575 mm^{-1} . This was then used to calculate a dose rate with the 8mm shield to verify our results.

To determine the total body effective dose, we used an active area of the detector of 20 cm^2 , which we also related to the area of skin and bone irradiated. The total skin area of an adult was assumed to be 18,000 cm^2 and approximately 11,000 cm^2 for a child aged 10 (Boniol et al. 2008). The total body bone area of an adult is approximately 2,200 cm^2 and a child aged 10 is approximately 1,300 cm^2 (Looker et al. 2013). Additionally, we assumed

a uniform beam and interactions with both sides of the leg, 40 cm² total with the tissue weighting factors for bone surface and skin according to ICRP 103 of 0.01 and 0.12 for bone marrow (ICRP. 2007). Finally, we conservatively assumed the same percentage of bone marrow irradiated as percentage of total bone surface, but, as bone marrow is not uniformly distributed among areas in the bone this should be a conservatively high estimate. Table 2 shows the final estimates for total body effective dose at different shielding thickness for adults and children.

DISCUSSION

Measurements were taken to show dose around the tube with the primary focus being the area in front of the tube. Considering there will always be a person in front of the tube receiving a measurement, the spatial measurements provide an excellent representation of the dose one can expect to receive during their scan. This approach allowed us to identify any gradients present to better reconstruct dose received. Furthermore, the scatter measurements taken around the x-ray tube allowed us to better understand the dose an operator will receive. This will help us identify the ideal location to place the operator to maintain dose as low as reasonably achievable (ALARA).

We were able to show that dose rate changes as expected by varying current and voltage. The linear relationship shown when varying current and the non-linear relationship when varying voltage displays that our setup did not alter x-ray tube output. Similar to previous studies of x-ray tube dosimetry (Specht et al. 2019c).

The scatter measurements show that adding bone and tissue phantoms increased the scatter around the source. For most degrees and distances, the measurements taken without bone and tissue phantoms had lower dose rates than measurements taken with bone or with bone and tissue. The measurements taken with bone and with bone and tissue were generally similar. Differences in values were insignificant as both showed an increase dose rate from scatter. Another explanation for the increased dose rate is ionization of the bone and tissue. These interactions in the bone and tissue would increase radiation to the surrounding area. Regardless of any phantoms present or distance from the beam, dose rates decreased as the degree from the beam increased. This shows that the safest place for a bystander to be during operations is behind the beam.

The spatial measurements consistently showed that the highest radiation field was directly in line with the x-ray tube. Bone did attenuate a significant amount of the radiation produced, and this attenuation was further amplified when bone and tissue were present. Additionally, higher radiation doses were seen around the tube with the bone, and bone and tissue setup. This suggests, and is consistent with other measurements taken, that scatter radiation is slightly increasing dose to the immediate surroundings. Furthermore, we saw that dose may not always be symmetrical to the left or the right of and above or below the beam. This is mostly likely due to an imperfect setup, representative of actual conditions that can be expected upon deployment.

The total body effective dose was found to be approximately 1.9 μSv and 3.2 μSv for an adult and child aged 10 years respectively with 8 mm of beam filtration using our molybdenum shield. This dose would represent a negligible radiation risk to the individual as the public dose limit is 1 mSv y^{-1} (US Nuclear Regulatory Commission 2023). One scan would thus be 0.2% and 0.3% for adults and children of Nuclear Regulatory Commission dose limit for a member of the public. Background sources represent approximately 3 mSv every year to which these scans would be 0.06% and 0.11% for adults and children respectively (Laura 2015). This is without consideration of the potential merits of measurement and surveillance of lead exposure in the participants being scanned. However, since this dose is localized solely to the extremities it is likely that this calculation of total body effective dose is still an overestimation of potential risk associated with the stochastic risks of the radiation. Compared to other diagnostic modalities, this dose is smaller than what is experienced by a chest x-ray, about 1/100th of the potential total body effective dose in comparison, and is consistent with the 3.1 μSv dose found in a previous study of a portable XRF system (Mettler et al. 2008; Specht et al. 2019c). Furthermore, with dose rates behind the tube being equivalent to background, we expect the dose received by the operator to be negligible.

CONCLUSION

In this study, we assessed the beam directionality, radiation doses, and occupational exposure to validate the safety and effectiveness of this approach. Using bone and tissue phantoms, we demonstrated the spatial dose variations, scattering effects, and attenuation coefficients linked to different shielding designs. The system demonstrated consistent output, showcasing distinct dose-rate relationships with varying current and voltage. The total body effective dose for an individual being scanned using the beam with 8 mm of molybdenum shielding was found to be 1.94 μSv and 3.28 μSv for an adult or child aged 10 respectively. The dose to the operator would be effectively zero if they are located behind x-ray tube. Thus, this device can be safely utilized for the monitoring of lead exposure and represents minimal dose to the operator as well as the individual being scanned.

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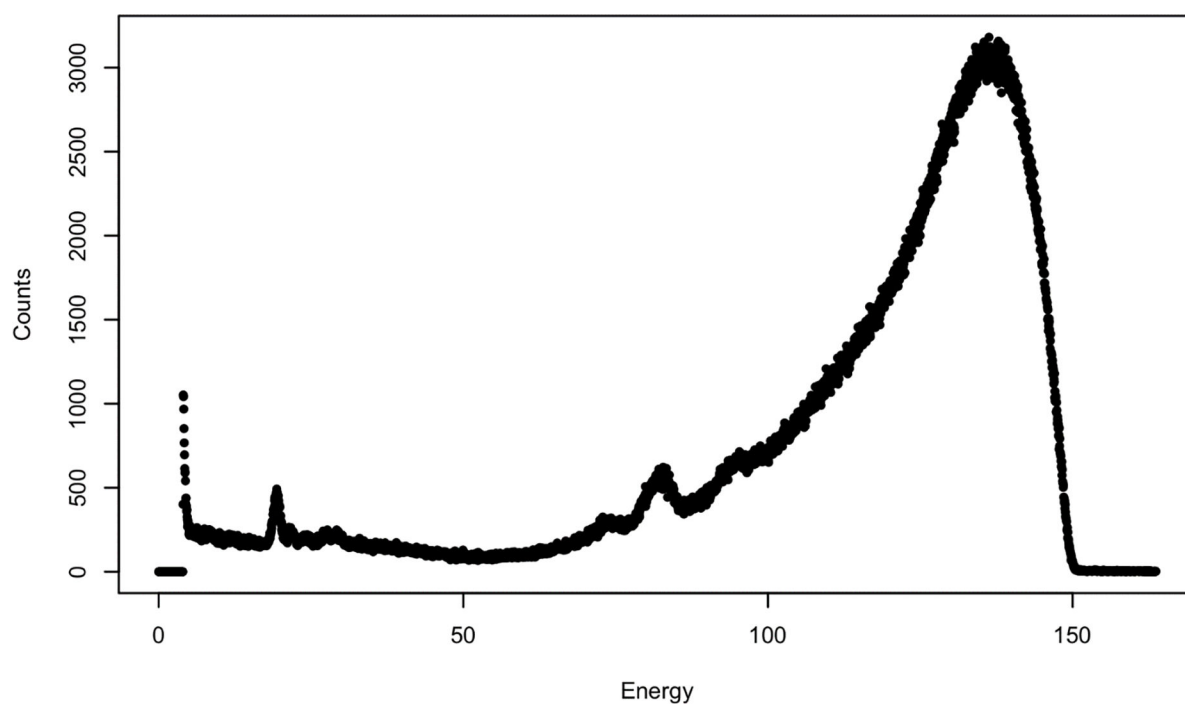


Fig. 1.
Spectrum Showing Total Counts at Various keV X-ray Energies

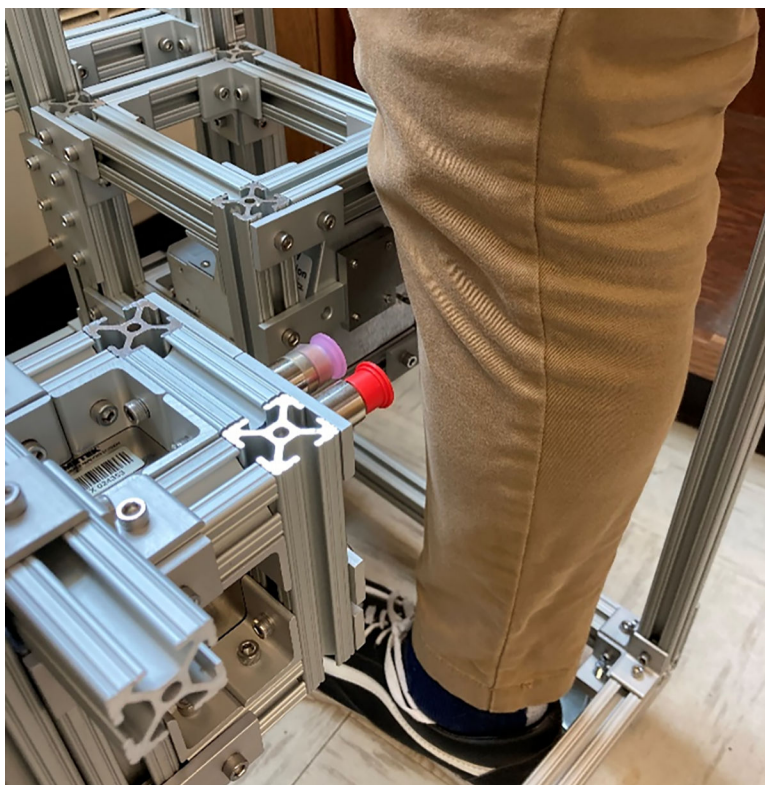


Fig. 2.
Designed Clinical Setup of the XRF Measurement System

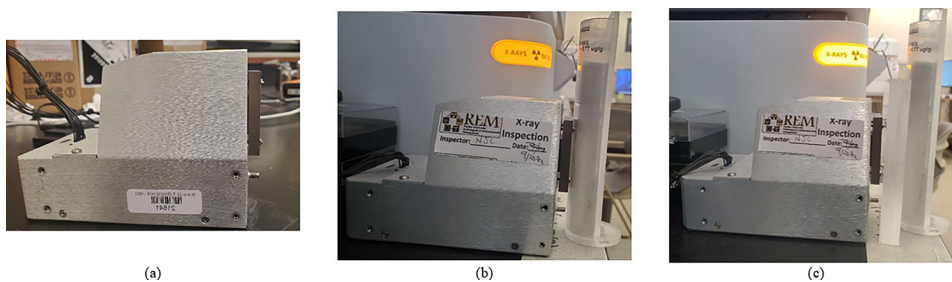


Fig. 3.
Experimental Setup of the X-ray Tube (a) with No Bone or Tissue Phantoms, (b) with Only Bone Phantom, and (c) with Bone and Tissue Phantoms

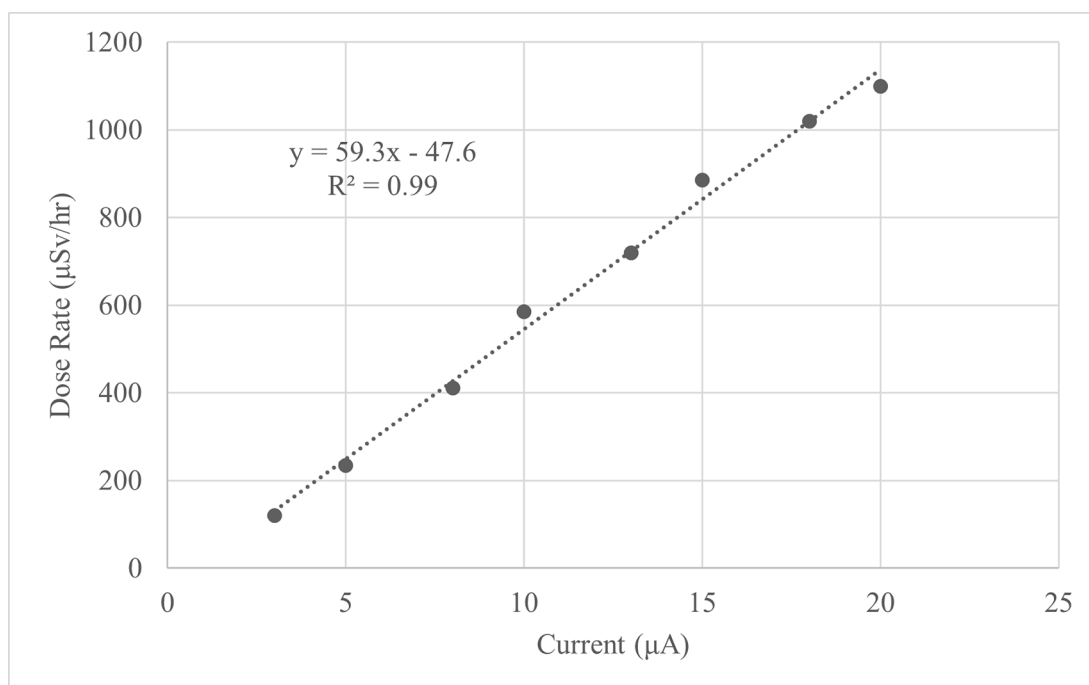


Fig. 4.
Measured Dose Rate Adjusting Current from 3 μA to 20 μA

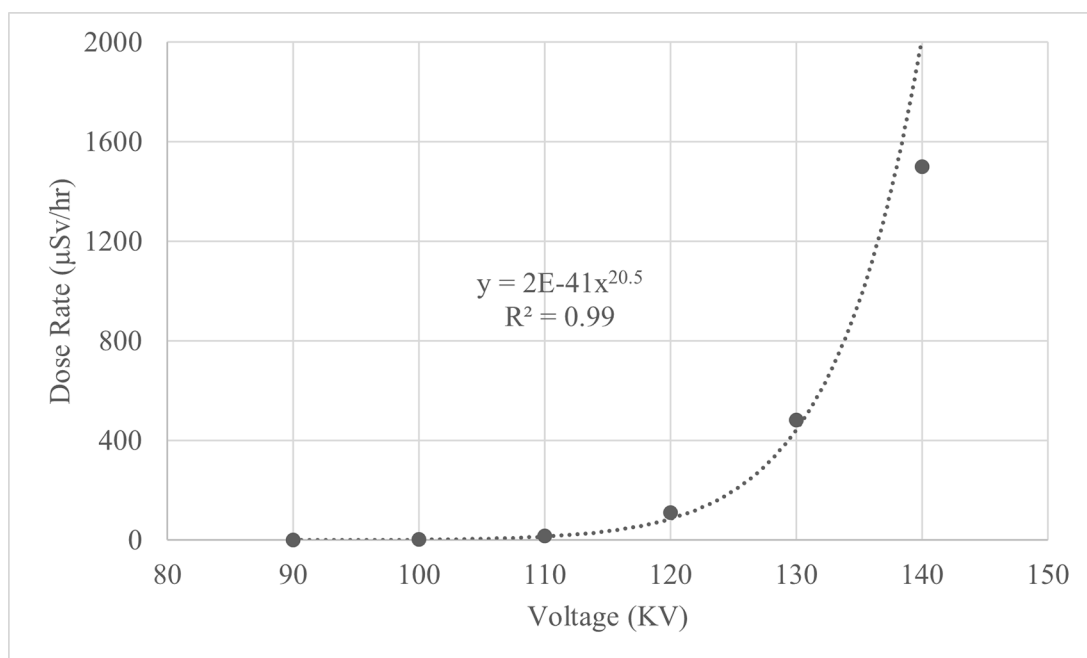


Fig. 5.
Measured Dose Rate Adjusting Voltage from 90 kV to 140 kV

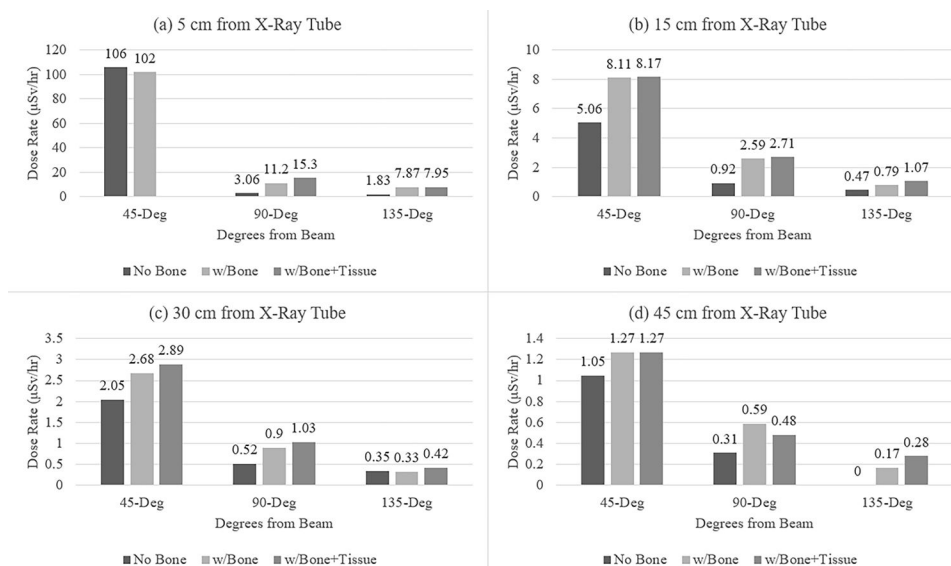


Fig. 6. Measured Dose Rate (a) 5, (b) 15, (c) 30, and (d) 45 cm from the X-ray Tube at 45, 90, and 135 degrees¹

¹Measurements not taken at 45-degrees with bone and tissue due to the setup preventing the meter from being this close.

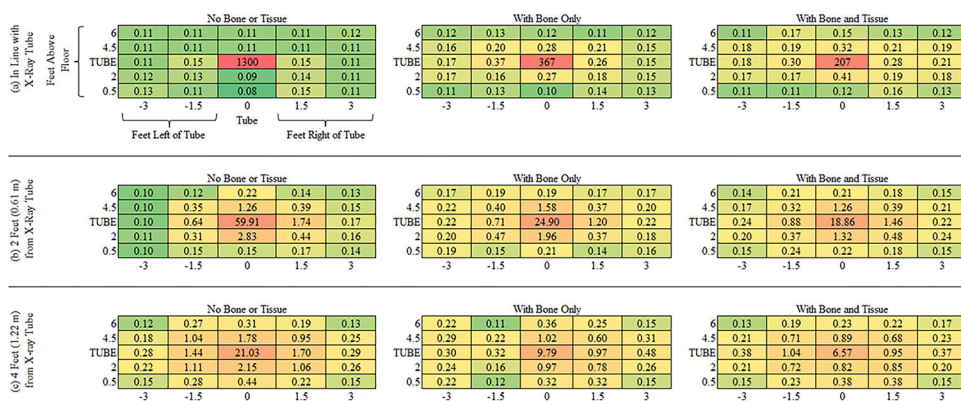


Fig. 7. Measured Dose Rates Taken in $\mu\text{Sv hr}^{-1}$ (a) in line with, (b) 2 Feet (0.61 m) from, and (c) 4 Feet (1.22 m) from the X-ray Tube

Table 1.

Measurements and Resulting Calculations to Determine the Effective Linear Attenuation Coefficient

Distance (cm)	Dose Rate with 10 mm shield ($\mu\text{Sv hr}^{-1}$)	Dose Rate with 8 mm shield ($\mu\text{Sv hr}^{-1}$)	Effective Linear Attenuation Coefficient (mm^{-1})	Calculated Dose Rate with 8 mm Shield ($\mu\text{Sv hr}^{-1}$)	Percent Difference Between Calculated and Actual Dose Rate with 8 mm Shield
15	229	765	0.603	743	3%
30	129	423	0.594	419	1%
45	78.4	245	0.570	254	4%
60	46.6	151	0.588	151	0%

Table 2.

Total Body Effective Dose for an Adult and Child Aged 10 Years at Varying Shield Thicknesses

Shield Thickness (mm)	Total Body Effective Dose (μSv)	
	Adult	Child Aged 10 Years
6	6.29	10.64
8	1.94	3.28
10	0.60	1.01
12	0.18	0.31