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Assessment of Scatter Radiation Exposure in Diagnostic X-Ray Procedures for Radiation Safety

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Abstract

Background: Radiation protection in medical X-ray imaging has been a subject of extensive scientific inquiry in recent decades. With diverse equipment and practices, attention has focused not only on patient doses but also on occupational exposure. Shielding requirements are crucial for safeguarding both medical personnel and those in the vicinity from scatter radiation, necessitating detailed investigation.

Aim: This study aimed to measure secondary radiation in a conventional radiographic setting, focusing on dose rates and their dependence on radiographic exposure factors such as tube voltage and distance. The research sought to provide insights that could optimize radiation protection for medical personnel and patients, especially in scenarios involving mobile X-ray equipment.

Methods: A conventional radiographic system was utilized, equipped with a diagnostic X-ray tube and a three-phase high-voltage generator. Measurements were conducted using an ionization chamber calibrated for ambient dose rate equivalent, positioned at various distances and angles from a cylindrical water phantom. The X-ray field was maintained constant at 40 x 40 cm^2 to simulate a worst-case scenario. Additionally, scatter X-ray energy distribution was evaluated through X-ray spectrometry.

Results: Measurements indicated that variations in the distance between the focal spot and the phantom minimally affected measured secondary radiation values. The study revealed a proportional relationship between scatter radiation dose rate and tube voltage, with a notable decrease observed with added aluminum filtration. Analysis also highlighted the significance of normalizing results per tube current for practical applications during mobile X-ray radiography.

Conclusion: The study underscores the importance of considering both distance and filtration strategies to mitigate secondary radiation exposure effectively. Results offer valuable insights for optimizing radiation protection protocols, emphasizing the importance of proper equipment setup and awareness of exposure factors. These findings contribute to enhancing safety standards in medical X-ray imaging, benefiting both healthcare professionals and patients alike.

Introduction

Over recent decades, significant scientific discourse has revolved around radiation protection and dosimetry within the realm of medical X-ray imaging. The variations in equipment and X-ray practices not only influence patient doses but also impact the exposure of personnel. Consequently, there has been considerable attention directed towards understanding and mitigating the effects of scatter radiation, particularly concerning shielding requirements to safeguard both occupational and living areas from its effects. (Fluke Biomedical, 2014)

In addition to shielding considerations, contemporary X-ray practices necessitate the evaluation of secondary radiation, particularly in close proximity to the X-ray tube. This knowledge is invaluable for radiographers conducting examinations with mobile radiography units, medical staff operating mobile fluoroscopic units, and even escorts assisting during procedures. Existing literature has delved into various studies measuring the exposure rate of secondary radiation emanating from X-ray equipment, focusing on computed tomography (CT) or calculating the scatter-to-incident radiation ratio. (Health Physics Society, 2014)

The primary objective of this study was to measure secondary radiation within a conventional radiographic room, quantifying the dose rate while examining the influence of radiographic exposure factors such as tube voltage and distance. Throughout the study, a large field size was maintained consistently. The findings of this investigation hold significance in optimizing radiation protection for medical personnel and patients in the vicinity, particularly during the use of mobile X-ray equipment. Furthermore, the study assessed the energy distribution of scatter X-rays through X-ray spectrometry, providing insights into the nature and characteristics of the scattered radiation. (PTW, 2014)

Materials and Methods

A conventional radiographic system (Philips Medio 65 CP-H) located in the Radiology Department , served as the primary equipment for this study. The system featured a three-phase high-voltage generator and a diagnostic X-ray tube capable of varying tube voltage from 40 to 150 kVp, tube current from 5 to 700 mA, and exposure time from 0.003 to 16 s. Notably, the half value layer (HVL) was measured at 3.2 mm Al for 80 kVp. To measure secondary radiation, an ionization chamber (451P-DE-SI Fluke Biomedical) calibrated for ambient dose rate equivalent H*(10) was utilized. The survey meter's response time was 2 seconds for dose rates ranging from 0 to 50 mSv h^-1.

The measurements were conducted in freeze mode. The accuracy of tube voltage and irradiation time was confirmed using a non-invasive X-ray test device (Diavolt Universal, PTW-Freiburg). Furthermore, the X-ray output was measured using a Diados E dosemeter with the radiation semiconductor detector Diados T60004, specifically suitable for tube voltages between 45 and 150 kVp.

A cylindrical water phantom with a 38 cm diameter was positioned on the radiographic table, maintaining a constant distance of 1.0 m between the tube focal spot and the center of the upper surface of the phantom. The X-ray field size remained consistent at 40 x 40 cm^2 to encompass the cylindrical phantom fully, representing a worst-case scenario for radiation protection considerations. The survey meter was situated at a height of 15 cm relative to the phantom base, facing the phantom's measuring surface. This setup allowed measurement of scattered X-rays from the phantom, walls, floor, and ceiling, as well as negligible leakage radiation from the X-ray tube.

A systematic study was undertaken to account for measurement errors arising from setup. The positioning of the phantom and survey meter relative to the X-ray tube and phantom, respectively, maintained a marginal error within 1 cm. Additionally, the survey's orientation with respect to the X-ray tube floor axis was within 1° marginal error. The uncertainty of the measurements, encompassing survey positioning, phantom positioning, survey reading error, survey calibration, survey measurements, and repeatability of X-ray tube output, was determined to be 6.4%.

The ambient dose rate equivalent H*(10) was measured for varying tube voltage values (60, 80, and 100 kVp, and 100 kVp with an additional 2-mm Al filtration), exposure time of 2.5 s, and tube current of 25 mA. For the case of 100 kVp with 2-mm Al filtration, the tube current was allowed to vary.

Furthermore, the X-ray scatter energy distribution was assessed using an Amptek XR-100 CdTe spectrometer positioned at a 90° angle to the phantom at a distance of 50 cm. The spectrometer was equipped with a collimator with a 0.2 mm diameter, selectively measuring scatter X-rays from the phantom.

Calibration corrections were applied to the spectrometer to adjust for energy per X-ray bin and its quantum efficiency (QE) response of the CdTe, obtained from the manufacturer's data sheet. The correction factor (CF) per energy was determined considering the X-ray interaction probabilities.

Results and Discussion

The study investigated the impact of various factors on measured secondary radiation values. It was found that deviations in the focal spot to phantom distance up to 2 cm did not significantly affect the measured secondary radiation values. Similarly, minor deviations of less than 1 cm in the placement of the survey meter relative to the phantom did not influence the results, with the verticality of the survey meter maintained consistently using a photographic stand. (Economides et al., 2007)

Total filtration of the X-ray beam was determined by measuring the half value layer (HVL). The measured HVL ranged between 2.7 and 4.6 mm Al, well within typical values. Table 1 presents the measured HVL and X-ray output for tube voltages under investigation, revealing a dependency of scatter radiation dose rate on the X-ray tube voltage used. The relationship was modeled by the equation (mSv h^-1) = 2 × 10^(-27) × (kVp)^3.853, with an R^2 value of 0.995. Additionally, Table 1 illustrates the dose rate per unit tube current (mSv h^-1 mA^-1) for a tube current of 25 mA, providing valuable insights for estimating ambient dose rate equivalent H*(10) for various X-ray tube voltages and exposure times. (Kalyvas et al., 2013)

Further analysis in Table 2 and Table 3 presents detailed dose rate measurements for specific X-ray tube voltages (60, 80, and 100 kVp) under varying irradiation conditions and distances from the phantom. Notably, at an angle of 3158 and a distance of 1.0 m, the dose rate significantly increases compared to other angles. Table 3 highlights corresponding results for tube voltage of 100 kVp with an additional 2.0-mm Al filtration, indicating lower dose rates compared to 100 kVp without filtration, thus affirming the proportionality of dose rate with milliampere. (Michail et al., 2011)

The scatter radiation X-ray energy distribution, reveals average energies ranging from 34.88 to 68.45 keV for different tube voltages and filtration conditions. These findings are crucial for personnel dosemeter calibration purposes. However, it's important to note that these measurements only account for scatter radiation from the phantom due to the collimator of the Amptek spectrometer, excluding secondary radiation from other surfaces and leakage radiation from the X-ray tube. (Tsalafoutas, 2006)

Table 1. The X-ray output, the X-ray beam HVL, the secondary dose rate and the dose rate per tube current for various tube voltages at 1.5 m, at 908 angle and 25 mA and 2.5 s.

Tube Voltage (kVp)	X-ray Output (mGy mAs^-1)	Calculated HVL (mm Al)	Secondary Radiation Dose Rate at 1.5 m, at 90° Angle (mSv h^-1)	Dose Rate Normalized at 25 mA [(mSv h^-1) mA^-1]
60	0.04	2.7	1.2	0.048
80	0.09	3.2	4.1	0.164
100	0.15	3.7	8.5	0.34
100 (with 2.0-mm Al)	0.10	4.6	7.0	0.28

Table 2. Secondary radiation dose rate with no added filtration for various distances, tube voltages and angles at tube current of 25 mA and exposure time of 2.5 s.

Angle of Scattered Radiation (degrees)		Secondary Radiation Dose Rate (mSv h^-1)						
Distance from the Phantom (m)	**Tube Voltage (kVp)**	**0**	**45**	**90**	**135**	**180**	**225**	**315**
1.0	100	19.0	19.0	18.5	19.5	18.5	18.5	22.0
1.5	100	8.0	8.0	8.5	8.0	8.0	—	—
2.0	100	4.5	4.9	4.5	4.9	4.9	—	—
1.0	80	8.5	8.0	8.5	8.0	8.0	8.5	9.5
1.5	80	4.0	3.8	4.1	3.9	3.9	—	—
2.0	80	2.3	2.3	2.5	2.3	2.3	—	—
1.0	60	2.5	2.5	2.6	2.4	2.4	2.5	2.8
1.5	60	1.1	1.1	1.2	1.1	1.1	—	—
2.0	60	0.7	0.7	0.7	0.6	0.6	—	—

Table 3. Secondary radiation dose rate with an additional filter of 2-mm Al at 100 kVp for various distances, tube currents and angles at exposure time of 2.5 s.

Angle of Scattered Radiation (degrees)		Secondary Radiation Dose Rate (mSv h^-1)						
Distance from the Phantom (m)	**Tube Current (mA)**	**0**	**45**	**90**	**135**	**180**	**225**	**315**
1.0	10	5.5	5.5	5.5	6.0	5.5	5.5	6.5
1.0	25	15.5	15.5	15.0	16.0	15.0	15.5	18.0
1.0	50	33.5	33.0	32.5	33.5	32.5	33.0	36.0
1.5	10	2.8	2.8	3.0	2.7	2.9	—	—
1.5	25	6.5	6.5	7.0	6.5	7.0	—	—
1.5	50	14.0	14.5	15.0	14.5	14.5	—	—
2.0	10	1.7	1.7	1.7	1.7	1.7	—	—

2.0	25	4.3	4.1	4.3	4.2	4.2	—	—
2.0	50	8.0	8.0	8.0	8.0	8.0	—	—

Conclusions

The study revealed that the dose rate in air decreases by approximately 0.40% for every half meter away from the phantom, while its angular distribution remained relatively stable due to the symmetry of the phantom setup. Furthermore, the addition of 2.0-mm Al filtration resulted in a significant reduction of the secondary dose rate by 21.4%, attributed to the corresponding decrease in X-ray tube output.

Normalizing the results per tube current, i.e., (mSv h^-1)/(mA), could provide valuable insights for medical staff during mobile X-ray radiography procedures. These findings underscore the importance of considering both distance and filtration strategies to effectively mitigate secondary radiation exposure in clinical settings.

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