Occupational radiation exposure of orthopedists at different locations during pedicle screw insertion: An anthropomorphic phantom study

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Abstract.
BACKGROUND: The purpose of this work was to evaluate orthopedic surgeons' exposure to occupational radiation doses from scattering using a mobile flat panel C-arm X-ray machine at different standing positions during an intraoperative pedicle screw implantation.
OBJECTIVE: Evaluate the radiation dose received by medical staff, by applying flat X-ray machine in surgical room during an intraoperative pedicle screw implantation.
METHODS: A mobile flat-panel C-arm X-ray machine at a dedicated orthopedic operating room was used to image an anthropomorphic female phantom which was set in a prone position on the operating table. The X-ray was projected horizontally, and 1 minute continuous fluoroscopy was used for lumbar spine and thoracolumbar spine during pedicle screw implantation. Scattering radiation doses to orthopedic surgeons were measured at different standing positions and body heights (50, 100, 150 cm above the ground) with and without limited collimations.
RESULTS: The dose area product (DAP) in this experiment is normalized as 343 μGy·m^2. In the four areas, the lowest scattered radiation measured by DF is 11.2 vs. 0.7 μSv, outside and inside the lead suit, respectively, with or without restricted field, 150 cm above the ground, and the lowest scattered radiation dose inside the lead suit. It is 1.3 vs. 0.5 μSv. Comparing the highest dose of the TF at with the lowest dose of the DF, the average result is 73.7 vs. 11.1 μSv, $P < 0.05$.
CONCLUSIONS: Using a mobile flat-panel C-arm X-ray machine during a pedicle screw implantation, the minimum scattering radiation to surgeons was found to be at the terminal DF area based on the analysis of the scattering doses orthopedic surgeons were exposed to.

Keywords: Fluoroscopy, pedicle screw insertion, effective dose, scattered radiation

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1. Introduction

The mobile C-Arm fluoroscopy is frequently used in orthopedic surgeries. X-ray is applied to ensure the accuracy of pedicle screw insertion (PSI) and percutaneous vertebroplasty (PVP) [1]. During PSI, the screw is inserted along the pedicle and kept away from spine cord and vertebrae. As a pedicle is surrounded by blood vessels and nerves, the screw may be mistakenly inserted to the intervertebral foramen and result in cerebrospinal fluid leakage, if without X-ray fluoroscopy [2]. Previous researches have pointed out that the error rate of PSI without X-ray is 12.7% to 16.7 [3,4], and the rate of nerve damage reaches up to 40% [4]. To improve the accuracy of PSI, fluoroscopy becomes a necessity, which will cause an increase in occupational radiation exposure of orthopedists.

With the development of medical imaging, X-ray is more widely used, and accompanying cancer risk on doctors is also increasing, which has aroused debates [5]. Thanks to fluoroscopy X-ray, the accuracy on spinal surgeries is improved [6], and spinal surgeries are easier to be conducted [7–11]. However, the risk of radiation exposure on orthopedist increases. To decrease the occupational radiation exposure and possible cancer risk on doctors, operators of X-ray machines should lower the necessary dose for examination, and doctors should obey As Low as Reasonably Achievable (ALARA) [12] during surgeries using fluoroscopy X-ray.

In this article, the Alderson Radiation Therapy (ART) phantom is used to simulate clinical scattered radiation impact in PSI. The doses of radiation exposure in TH, TF, DH and DF sides are measured and discussed. The examine points are 50, 100 and 150 cm above the ground, representing the knees, chest, and thyroid of orthopedist respectively.

2. Materials and methods

2.1. ART anthropomorphic phantom

The ART anthropomorphic female phantom is used to simulate a female lying on her stomach. The weight and height are 155 cm and 50 kg respectively. The legs are not counted. The density structure of phantom is highly similar to human bone and soft tissue [13,14]. Thus, the phantom experiment can reflect the real clinical scattered radiation impact.

2.2. Ion chamber dosimeter

The dosimeter adopted is Fluke Biomedical model 660-5DE 400-cc (Everett, USA), and the display unit is μGy. The background radiation dose in the operating room is 0.06 μGy/min. The ionizing radiation unit is Gy, representing the absorbed dose during measurement. The unit of energy loss in ionizing radiation of object per kilogram is J/kg. The dose of ionizing radiation received by person exposed in radiation is Sv. The different biological effects caused by different rays, energies, and weighting factor of radiation have been considered. When detecting scattered radiation was measured using a fluke biomedical model 660-5DE dosimeter 400 cc ion chamber. According to the results of the Taiwan Institute of Nuclear Energy Research, the corrected value of this instrument was 0.5966.

2.3. Experiment design and X-ray machine settings

This study was approved by the Chang Gung Memorial Hospital, Taiwan and approval was granted by the Chang Gung Hospital Institutional Review Board under numbers 201601278B0 and 201900121B0. All the data was collected in one surgery room at Kaohsiung Chang Gung Hospital, Taiwan.

The radiation doses received by the orthopedist while using fluoroscopy X-ray in lumbar vertebrae PSI
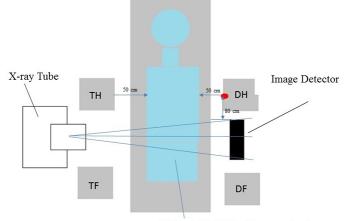
Fig. 1. The X-ray machine settings.

are measured in the same operating room. The phantom is lying on stomach side on operating table with lumbar vertebrae exposed. The position of phantom is fixed despite the change of exposure areas. The position where orthopedist most often stand is shown in Fig. 1. Suppose orthopedist wears 0.5 mmPb lead aprons and lead thyroid shied, and stands as close as possible to the patient. The mobile X-ray machine adopted is Cios Alpha (Siemens AG, Healthcare Sector, Erlangen, Germany). The X-ray is horizontally projected to achieve lateral image of lumbar vertebrae. Orthopedist stands by patient foot side. The X-ray is projected from left to right. The cathode side of the X-ray tube points to ceiling and the anode side of X-ray tube points to the ground. The center of the X-ray projector is 109 cm above the ground. Image plate is 30*30 cm. Anode target angle is 10 degree. Focal length is 0.3 and the original filter is 3 mmAl/0.1 mm Cu. Detector pulse is 40 nGy. The fluoroscopy is under automatic dose rate control (ADR) and automatic exposure control (AEC). The system automatically adjusts the kV/mA and kV/mAs value. The X-ray protects continuously for 10 seconds. And the scattered radiation doses in TH, TF, DH and DF are measured.

2.4. The measure points of scattered radiation

To measure the scattered radiation dose on orthopedist during surgery, we chose the measure point 50 cm away from patient skin, and 80 cm away from tube shell and plate. As shown in Fig. 2, a square of 40*40 cm on the ground is marked as the orthopedist standing point during surgery. The scattered radiation measure section is from TH to TF and DH to DF. The observer stands by the patient foot side. The X-ray is horizontally projected from left to right. The red point is the measure point.

As shown in Fig. 3, the operation desk is 100 cm above the ground, which satisfies the requirement of surgery and lowest height of C-arm horizontal projection. In four sections, the scattered radiation doses are measured separately in front of lead suit and in the lead suit. The measure points are 50 cm, 100 cm and 150 cm above the ground, representing knees, chest and thyroid respectively. The measurements repeated for five times. We compared the radiation exposure differences when using the full X-ray projection area of 40 m^2, and controlled X-ray projection area of 20 m^2, which keeps only spine observable. After each fluoroscopy, the DAP is displayed on the X-ray machine screen. The average DAP when using full X-ray projection area is 166.5 ± 2.9 μGym^2 while one when using the controlled X-ray projection area is

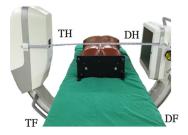Fig. 2. Scattered radiation experiment using ART phantom.

Fig. 3. The orthopedic surgeon's standing positions during surgery.

$109.7 \pm 2.3 \ \mu \text{Gym}^2$. The research compares three factors that may influence the scattered radiation dose. Firstly, different scattered radiation doses are measured based on different heights above the ground of the measure points. Secondly, different scattered radiation doses are measured based on different standing points of orthopedist. Thirdly, the different scattered radiation doses are measured based on projection areas.

2.5. Statistical analysis

The scattered radiation doses on the X-ray tube side and image detector side were compared using paired T tests. The paired T tests reflected that occupational radiation exposure is related with orthopedist location during PSI. $P < 0.05$ was regarded as statistically significant. Statistical analysis was performed using SPSS version 22.0 (IBM, Armonk, NY, USA).

3. Results

The research adopted ART phantom to simulate scattered radiation received by orthopedist during spine surgeries. The measure point is 50 cm away from patient skin, and 50 cm, 100 cm, and 150 cm above the ground, representing the knee, chest and thyroid respectively. The X-ray is horizontally projected. The radiation doses inside and outside the 0.5 mmPb lead suit are measured. The nature background

Table 1
Radiation dose in different sections

Location	Height (cm)	Tube voltage ev	Without protection of lead suit μGy	With protection of lead suit μGy	Attenuation rate (%)
TH	50	93	9.9 ± 0.1^a	0.4 ± 0.0^a	96.0%
	100	93	116.3 ± 1.0	1.1 ± 0.0	99.1%
	150	93	68.9 ± 0.4	17.8 ± 0.0	74.2%
TF	50	93	4.5 ± 0.2	0.2 ± 0.0	95.6%
	100	93	128.0 ± 0.6	1.4 ± 0.0	98.9%
	150	93	88.5 ± 0.5	15.0 ± 0.1	83.1%
DH	50	93	5.2 ± 0.0	0.4 ± 0.0	92.3%
	100	93	5.2 ± 0.0	0.3 ± 0.0	94.2%
	150	93	24.7 ± 0.1	3.3 ± 0.0	86.6%
DF	50	93	6.6 ± 0.1	0.4 ± 0.0	93.9%
	100	93	4.7 ± 0.1	0.3 ± 0.0	93.6%
	150	93	22.2 ± 0.1	1.3 ± 0.0	94.1%

[a]Data are means $\pm$ standard deviations.

Table 2
Paired T test analysis identified predictors of
orthopedists and showed that DF received the
lowest scattered radiation

Location area	Paired T test
Tube and image detector	$P < 0.05$
DF–TH	$P < 0.05$
DF–DH	$P > 0.05$
DF–TF	$P < 0.05$

radiation in operation room is 0.06 μSv/min. According to the clinical data, the average dose area is 343 μGym^2, so we set the DAP in experiment as 343 μGym^2. The radiation dose inside lead suit is considered as occupational radiation dose. In Table 1, when the orthopedist stands in DF, the received scattered radiation is lowest. The overall radiation dose in TF is 6.6 times that in DF. In Table 2, when $P < 0.05$ (paired T test), standing in DF section can reduce the radiation exposure rate effectively.

The estimated air kerma dose can be calculated by a simplified version of Eqs (1)–(4):

$$\text{TH Dose(air kerma)} = 18.8(\text{nGy}/\mu\text{Gym}^2) \times \text{DAP}(\mu\text{Gym}^2) \tag{1}$$

$$\text{TF Dose(air kerma)} = 16.1(\text{nGy}/\mu\text{Gym}^2) \times \text{DAP}(\mu\text{Gym}^2) \tag{2}$$

$$\text{DH Dose(air kerma)} = 3.9(\text{nGy}/\mu\text{Gym}^2) \times \text{DAP}(\mu\text{Gym}^2) \tag{3}$$

$$\text{DF Dose(air kerma)} = 1.9(\text{nGy}/\mu\text{Gym}^2) \times \text{DAP}(\mu\text{Gym}^2) \tag{4}$$

The controlled X-ray projection area can improve the image contrast, however the scattered radiation is increased. Table 3 shows the difference of radiation doses between the full X-ray projection area and controlled X-ray projection area at the point 150 cm above the height. If the tube voltage in controlled X-ray projection area increases, the scattered radiation is more penetrable, and radiation dose in TF is the most. The scattered radiation inside lead suit in TH section in the controlled X-ray projection is 17.8 Sv, while in uncontrolled one is 19.8 Sv; in TF the rate is 15.0:20.4 Sv; in DH the rate is 3.3:1.3 Sv; in DF the rate is 1.3:1.7 Sv. Use the paired T test $P < 0.05$ to represent that the controlled X-ray projection area cannot reduce the scattered radiation effectively. Scattered radiation penetration rate through the lead suit is 12.1% in tube side and 7.3% in image detector side. The lead suit can attenuation 90% of scattered radiation as a whole.

Table 3
The difference of radiation doses between full X-ray projection area and controlled X-ray projection area 150 cm above the height

Location	Height (cm)	Tube voltage ev	Without protection of lead suit μGy	With protection of lead suit μGy	Attenuation rate (%)
TH	150	93	68.9 ± 0.4[a]	17.8 ± 0.0[a]	74.20%
	[b]150	104	85.2 ± 0.6	19.8 ± 0.2	76.80%
TF	150	93	88.5 ± 0.5	15.0 ± 0.1	83.10%
	[b]150	104	102.2 ± 0.5	20.4 ± 0.3	80.00%
DH	150	93	24.7 ± 0.1	3.3 ± 0.0	86.60%
	[b]150	104	25.3 ± 0.1	1.3 ± 0.0	94.90%
DF	150	93	22.2 ± 0.1	1.3 ± 0.0	94.10%
	[b]150	104	20.0 ± 0.1	1.7 ± 0.0	91.50%

[a]Data are means $\pm$ standard deviations. [b]150 is the controlled X-ray projection area where only spine is observable.

4. Discussion

The research studied the scattered radiation dose received by orthopedists during spinal surgery using horizontal fluoroscopy X-ray machine. The experiment adopts ART phantom to simulate real clinical exposure environment and patient posture. The observer stood by the patient's feet, and the X-ray was horizontally projected from left to right. The scattered radiation dose may change with settings of X-ray exposure and the size of phantom. So, the experiments were conducted in the same operation room to avoid errors. This research focuses only on scattered radiation dose received by orthopedists during horizontal fluoroscopy on lumbar vertebra, because the scattered radiation in lumbar vertebra surgery is higher than surgeries on other body parts.

4.1. Comparisons to other studies

Previous researches show that when the X-ray is projected up and down, the radiation exposure with thyroid shields is 1.78 Sv/min while that without thyroid shields is 16.32 Sv/min [15]. Thyroid shields can block 85% of radiation. In our experiment, the X-ray is horizontally projected, and the measure point 150 cm above the ground represents thyroid. As shown in Fig. 1, when wearing the thyroid shied, the block rate on the tube side is 79% and on the image detector side is 90%. In the study by Sung, scattered radiation dose received by the surgeon's thyroid is 7 μSv/min during surgery using X-ray without the protection of thyroid shield. The study suggests that surgeons should wear a thyroid shied and the fluoroscopy duration should be no more than 1774 min [16]. In Lee's study, the scattered radiation dose received by the orthopedist's thyroid is 1.7 μSv/min during spinal surgery using X-ray. Lee suggested that the thyroid fluoroscopy duration should be no more than 18385 min [15]. In our simulation experiment, we compared the radiation doses inside lead suit in TH, TF, DH and DF sections, the values are 17.8 μGy, 15.0 μGy, 3.3 μGy and 1.3 μGy respectively. The highest value is 15 times of the lowest value. Though it is proven that larger distance between orthopedist and patient can reduce the radiation exposure, in spinal surgeries, orthopedist cannot be too far away from patient because the screw must be inserted along pedicle. So, we would suggest orthopedist to stand in DF section in continuous fluoroscopy. Besides, we measured the radiation 150 cm above the ground wearing thyroid shield when reducing the fluoroscopy area. Since fluoroscopy is under AEC, the mA is 0.2, but kVp increases from 93 kVp to 104 kVp, making the radiation more penetrating. When the fluoroscopy is reduced from 40 cm^2 to 22 cm^2, the scattered radiation doses in DF section reduce, while it increases in the other three sections. Although reducing

the fluoroscopy area can decrease the radiation absorbed by patient abdomen, it increases the radiation dose on spine. It cannot reduce the scattered radiation dose received by orthopedist. In conclusion, when fluoroscopy is under AEC, reducing fluoroscopy area will lead kVp increase, thus it cannot reduce the scattered radiation. Whether the scattered radiation can be reduced when the fluoroscopy area is controlled to 90 kVp, will be examined in further experiments.

Suppose the experiment result is applied in clinic and the radiation in air goes directly to thyroid, orthopedist will receive radiation of 15 μSv in one operation standing in TF section. According to the suggestion of The National Council on Radiation Protection and Measurements 116 that radiation doses received by the thyroid should be limited to 300 mSv in one year [17], orthopedists can conduct 20,000 operations each year. Although the dose is limited, the stochastic effects cannot be ignored.

4.2. The research limitations

In this research, only one type of lead suit is applied, so we did not compare the blocking rates of different types and different materials of protection suits. According to Scuderi et al., lead suit is too heavy to wear, so less heavy materials are proposed to be the substitutes. The blocking rate of three kinds of protection suits using un-lead materials are evaluated under the fluoroscopy X-ray (energy range 60–110 keV). When energy is less than 70 keV, the penetration rate of 0.254 mm lead aprons is 5.4%. The average penetration rate of 0.25 mmPb lead equivalent is 7.1%. When energy is less than 100 keV, the penetration rate of 0.508 mm lead aprons is 5%. The average penetration rate of 0.5 mmPb lead equivalent is 4.9% [18]. The entrance skin dose is not recorded in our X-ray exposure anthropomorphic phantom study. The patient dose can be obtained through a simple conversion formula, which is 0.065 mSv/Gy cm^2 (ICRP 103) [19].

The limitations in this research have been considered. Firstly, the X-ray machine is under ADR, which is more common in clinical applications. The scattered radiation under manual X-ray is not compared. The body thickness varies per patient. Although the dose can be manually adjusted, the patient will receive more doses in repeated check before the ideal setting is found, which may result in longer surgery and anesthesia duration, and increase the risk. Even though a manual X-ray can reduce the scattered radiation, it prolongs the anesthesia duration and reduces the image quality. So ADR is preferred in clinic rather than manual X-ray. Secondly, the reason why we did not use TLD to collect all scattered radiation in the first exposure is because TLD is unstable when the dosimeter is lower than 1 cGy [20], and is easily influenced by background radiation. In this research, fluoroscopy continuously works for 10 s and the lowest scattered radiation value in front of lead suit is 4.7 μGy, while the average daily background radiation in Taiwan is 3.5 μGy tested by TLD. When using TLD, the value can be easily affected by background radiation and the result can be underestimated if the value is not read immediately. Thirdly, the ART phantom has no head, leg or shank, so the scattered radiation may be under- or overestimated. However, since the influence is very limited, the result of this research can provide a reference to clinical applications.

5. Conclusions

In this study, we used the lead apron with 0.5 mmPb lead equivalent which only covers the front part of body. The penetration rate is 6.6% at 50 cm above the ground, 3.5% at 100 cm, and 15.5% at 150 cm. At 150 cm, the average controlled fluoroscopy area is 14.2%. The average penetration rate of 0.5 mmPb lead equivalent under 100 keV is 8.2%. Horizontal fluoroscopy X-ray is adopted in spinal surgeries, and

the X-ray machine is set as AEC to guarantee image quality. According to the comparison of scattered radiation doses in TH, TF, DH, and DF sections, we conclude that the dose in DF section is lowest. Thus, we suggest that orthopedists should conduct operations in DF section to minimize occupational radiation exposure. Overall, orthopedists receive the least scattered radiation dose when standing in DF section during spinal surgery.

Acknowledgments

Conflict of interest

None to report.

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