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Effect of metallic tools on scattered radiation dose during the use of C-arm fluoroscopy in orthopaedic surgery

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ABSTRACT

This study investigated the effect of metallic tools on the scattered radiation dose delivered to surgeons' radiosensitive organs while simulating hip surgery using C-arm fluoroscopy. Two phantoms, a pelvis and a Rando phantom, were used to simulate a patient and a surgeon in this study. Photoluminescence dosimeters were inserted into the Rando phantom in the positions of the eye, thyroid and gonad. A drill was positioned above the hip of the pelvis phantom or beside the pelvis phantom of the same height. For each drill location, the scattered radiation dose was measured when the angle to the operator phantom was 45°; this was repeated when the angle was 90°. The scattered radiation doses to the eye, thyroid and gonad when the drill was placed beside the pelvis phantom with 90° angulation to the operator phantom were significantly lower than the reference values and those when the drill was placed beside the pelvis phantom at a 45° angulation to the operator phantom. The scattered radiation doses to the eye and thyroid when the drill was placed above the hip were significantly lower than the references values. Of the four different scenarios, the scattered radiation doses to the eye, thyroid and gonad were lowest when the drill was placed beside the pelvis phantom with 90° angulation. This study showed that the scattered radiation doses to radiosensitive organs were affected by the location and angle of the metallic tools in relation to the operator. Therefore, orthopedic surgeons should consider the effect of metallic tools on the scattered radiation dose during intraoperative use of C-arm fluoroscopy.

Keywords: scattered radiation dose; radiosensitive organ; C-arm fluoroscopy; metallic tool

INTRODUCTION

C-arm fluoroscopy has been widely used intraoperatively by orthopedic surgeons because it can display real-time moving images of skeletal structures [1–3]. This capability provides considerable temporal anatomical information [4, 5]. For instance, surgeons can confirm the reduction of fractures and guide the accurate placement of radio-opaque implants [1]. Furthermore, C-arm fluoroscopy can make minimal invasive surgery possible [6]. These benefits result in early functional recovery, shorter hospital stay, and consequently, lowered medical costs [1].

However, as the use of C-arm fluoroscopy has increased, concerns have been raised regarding the amount of radiation received during the use of C-arm fluoroscopy [7–9]. The deterministic and stochastic effects of radiation on the human body are well known [10]. Gonads, bone marrow, breasts, cornea, gastrointestinal tract, lungs and thyroids are known to be radiosensitive organs at risk when performing intraoperative C-arm fluoroscopy [2, 11].

Several studies have investigated the scattered radiation doses received by the operator during C-arm fluoroscopy. They have shown

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that the following factors could reduce radiation exposure during the intraoperative use of C-arm fluoroscopy [1, 2, 8, 12–18]: (i) use of a mini C-arm instead of the conventional C-arm; (ii) avoidance of direct exposure to radiation; (iii) proper configuration of the C-arm; (iv) distance between the C-arm and the surgeon; (v) use of radioprotective equipment; (vi) shortened exposure time; (vii) placing a shielded screen between the radiation source and the surgeon; (viii) rotating the surgeon's eyes away from the patient; (ix) use of a scattered radiation protector; and (x) use of noise reduction technology.

Metallic tools such as drills, a mallet or implants are frequently used during orthopedic surgery, and surgeons usually confirm the location of the implant by using C-arm fluoroscopy. The use of these metallic tools can increase the scatter radiation dose to surgeons' radiosensitive organs. However, no studies have investigated the effect of metallic tools on scatter radiation dose. Therefore, we performed this study to investigate the effect of metallic tools on the scattered radiation dose delivered to surgeons' radiosensitive organs while simulating hip surgery using C-arm fluoroscopy.

MATERIALS AND METHODS

This study was exempted from the approval of our institutional review board because it involved no human subjects.

Two phantoms, a pelvis and a Rando phantom, were used to simulate a patient and a surgeon in this study. The anthropomorphic pelvis phantom (RS-113; Radiology Support Devices, Long Beach, CA, USA) that was used to simulate the patient was placed on the operating table. The pelvis phantom was composed of a cadaver bone surrounded by soft tissue–equivalent acrylic material. Thus, it had approximately the same density as human soft tissue. A C-arm fluoroscopy unit (OEC 9800; GE Healthcare, Milwaukee, WI, USA) was positioned beside the pelvis phantom at a 90° angle in the standard posteroanterior (PA) configuration (with the X-ray tube placed downward and the detector placed upward). The distance between the pelvis phantom on the operating table and the X-ray tube was 40 cm, and that between the pelvis phantom and the detector was 23 cm. The fluoroscopic screen was focused on the left femoral head. The C-arm fluoroscopic operating parameters were 80 kVp and 5.00 mA. The Rando phantom (ART200–5; Radiology Support Devices, Long Beach, CA, USA) that simulated the surgeon was placed beside the pelvis phantom at a distance of 40 cm. The Rando phantom was placed at an angular position of 90°(on the opposite side of the C-arm fluoroscope) to simulate an operator. The height of the operator phantom was adjusted to 162 cm to simulate a standing position (Fig. 1a).

Photoluminescence dosimeters (GD-352M; AGC Techno Glass, Tokyo, Japan), each of which had a Tin ($_{50}$Sn) filter in the capsule for low-energy compensation, were inserted in the Rando phantom at the positions of the eye, thyroid and gonad so that the radiation exposure could be measured in the most critical regions of the surgeon's body. The photoluminescence dosimeters were placed 10, 24 and 79 cm from the top of the head to represent the surgeon's eye, thyroid and gonad (Fig. 1b). Photoluminescence dosimeters were positioned with the same orientation and perpendicular to the ground to minimize the variation.

First, a lead plate ($225 \times 175 \times 2$ mm^3) as a positive control was placed between the detector and the pelvis phantom. Scattered radiation doses delivered to the radiosensitive organs

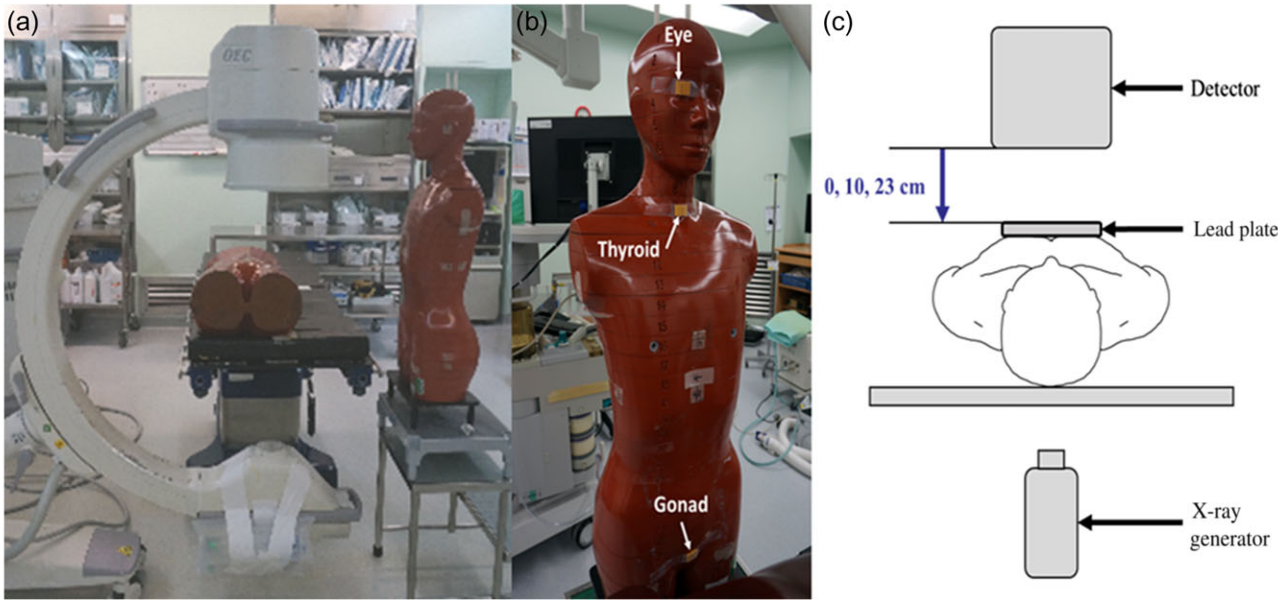

Fig. 1. Experimental set-up for radiation dose measurements. (a) Rando phantom (surgeon) is located at an angular position of 90°, and the C-arm fluoroscopy is in the standard PA configuration. (b) The photoluminescence dosimeters were placed 10, 24 and 79 cm from the top of the head to represent the surgeon's eye, thyroid and gonad. (c) The lead plate is placed between the detector and the patient phantom.

were measured from three different distances between the lead plate and the detector, which were 0, 10 and 23 cm (Fig. 1c). As reference values, scattered radiation doses were also measured without the lead plate.

Thereafter, a Drill (ACCULAN GA612; Aesculap, PA, USA) was used to simulate orthopedic surgery. The scattered radiation dose was measured while the drill was placed above the hip of the pelvis phantom or beside the pelvis phantom at the same height. For each drill location, the scattered radiation dose was measured while the angle to the operator phantom was 45°; this was repeated when the angle was 90°. Thus, the scattered radiation doses to the radiosensitive organs were measured in four different scenarios according to the location and orientation of the drill (Fig. 2).

The pelvis phantom was exposed to the radiation source for 10 min, with operator phantoms placed together. The surface radiation doses accumulated in the photoluminescence dosimeters located at the eye, thyroid and gonad of the operator phantom were measured. Each experimental scenario was repeated 20 times, and an average absorbed radiation dose per minute was calculated.

Statistical methods

The Kolmogorov–Smirnov test was used to verify the normality of the distribution of the continuous variables. One-way analysis of variance used to analyze the differences in scatter radiation doses to sensitive organs according to the location and orientation of the drill, and the distance between the detector and the lead plate. Multiple comparison tests were performed using Bonferroni corrections. All statistical analyses were performed using SPSS ver. 22.0 (SPSS, Inc., Chicago, IL, USA). All statistics were two-tailed, and P-values of < 0.05 were considered significant.

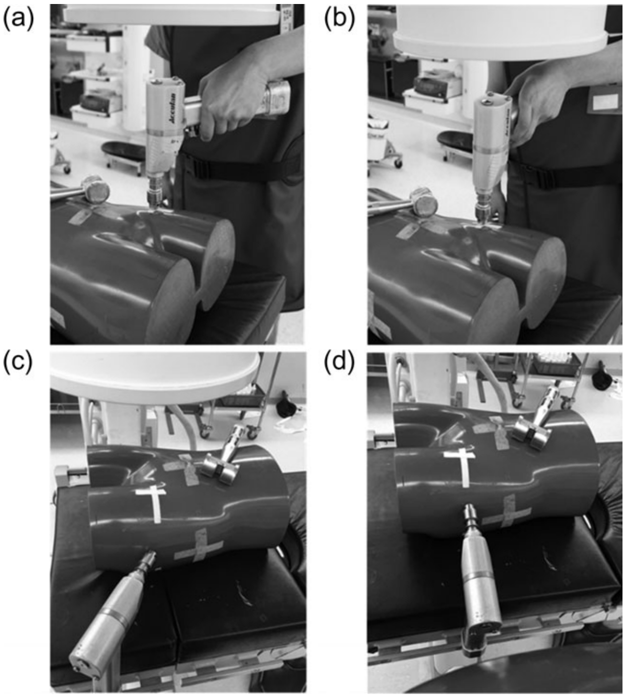

Fig. 2. Configuration of the experiments for the direction and position of the drill at (a) 45° and (b) 90° angulation to the operator phantom above the hip of the pelvis phantom, and (c) 45° and (d) 90° angulation to the operator at the same height as the pelvis phantom.

RESULTS

When no metallic tool was present, the scattered radiation doses to the gonad (80.1 μGy/min) were significantly higher than those to the eye and thyroid (28.7 and 42.6 μGy/min, respectively; $P < 0.001$). Scattered radiation doses to the eye and thyroid were highest when the distance between the lead plate and detector was 10 cm and lowest when the distance was 23 cm. Scattered radiation doses to the gonad were highest when the distance between the lead plate and detector was 10 cm and lowest when the lead plate was absent (Fig. 3).

Scattered radiation doses to the eye, thyroid and gonad when the drill was placed beside the pelvis phantom at a 90° angulation to the operator phantom were significantly lower than the reference values (all $P < 0.001$) and those when the drill was placed beside the pelvis phantom with 45° angulation to the operator phantom (all $P < 0.001$). The scattered radiation doses to the eye and thyroid when the drill was placed beside the pelvis phantom with 45° angulation to the operator phantom were significantly lower than the reference values ($P = 0.010$ and < 0.001, respectively). However, the scattered radiation dose to the gonad when the drill was placed beside the pelvis phantom with 45° angulation to the operator phantom was significantly higher than the reference values ($P < 0.001$). The scattered radiation doses to the eye and thyroid when the drill was placed above the hip with 90°($P = 0.001$ and < 0.001, respectively) or 45°($P < 0.001$ and 0.001, respectively) angulation to the operator phantom were significantly lower than the references values. However, the scattered radiation dose to the gonad when the drill was placed above the hip with 90° or 45° angulation to the operator phantom was significantly higher than the references values (all $P < 0.001$). No significant differences in the scattered radiation doses to the eye, thyroid or gonad were found when the drill was above the hip with 90° angulation to the operator compared when it was above the hip with 45° angulation to the operator phantom (all $P = 1.000$). Of the four different scenarios, the scattered radiation doses to the eye, thyroid and gonad were lowest when the drill was placed beside the pelvis phantom with 90° angulation to the operator phantom (Fig. 4).

DISCUSSION

To our knowledge, the current study is the first investigation regarding the effect of metallic tools on scattered radiation dose to radiosensitive organs during the use of C-arm fluoroscopy. This study demonstrated that the scattered radiation doses to radiosensitive organs were affected by the location and orientation of the metallic tools. We believe that the results of this study can facilitate the formulation of guidelines regarding the use of metallic tools during orthopedic surgery.

Before discussing the implications of the current study, some limitations of the study should be addressed. First, the fluoroscopic beam was focused on the left hip to simulate hip surgery in this

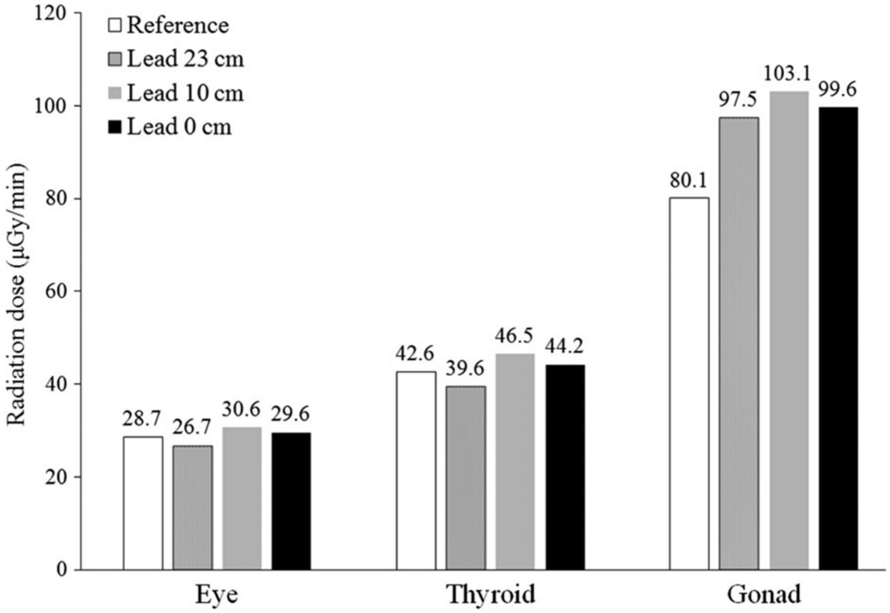

Fig. 3. Comparison of the scattered radiation doses delivered to the eyes, thyroid and gonad of the operator phantom according to the distance between the lead plate and the C-arm detector.

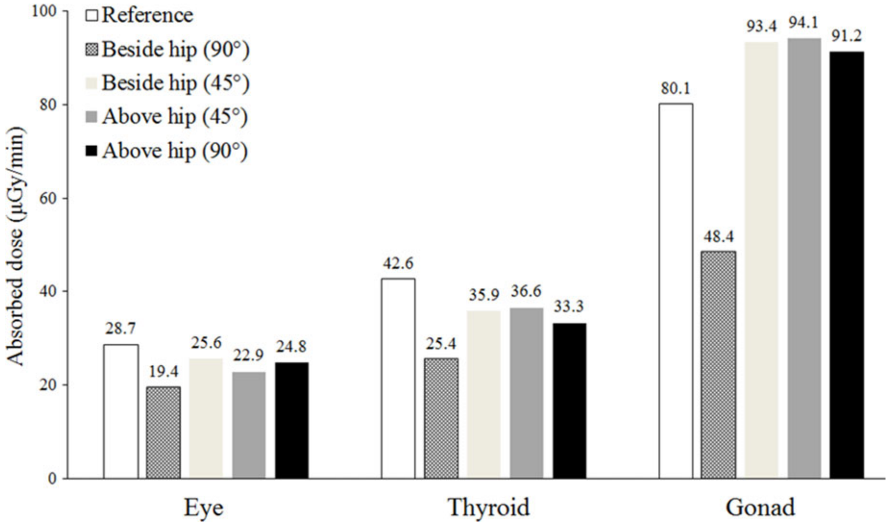

Fig. 4. Comparison of scattered radiation dose delivered to radiosensitive organs according to the location and direction of the drill.

study. Therefore, the results may not be applicable to various other orthopedic procedures. Second, the scattered radiation dose to an operator while wearing protective garments was not evaluated, even though most surgeons use protective garments during an operation. This study was focusing on the effect of metallic tools on scattered radiation dose. Further study on this issue is required.

Scattered radiation dose by pure metals has been known to be strongly affected by their atomic numbers [19–23]. Farahani *et al.* investigated the scattered radiation doses near metal and dental material interfaces irradiated with X- and gamma-ray therapy beams [19]. They showed that the backscatter dose was greatest for 18-carat gold alloy, followed by Ag–Hg amalgam, Ni–Cr alloy, tooth, and polystyrene, but the forward-scatter dose was lowest for 18-carat gold alloy and Ag–Hg amalgam, followed by Ni–Cr alloy, tooth, and polystyrene. In our experiments, the scattered radiation dose to radiosensitive organs when the drill was placed between the pelvis phantom and the detector was lower than that with a lead plate, which indicated that the backscatter dose from lead was higher than that from titanium. We think the reason for these findings is that the atomic number of the lead ($_{82}$Pb) is higher than that of the titanium ($_{22}$Ti).

Regardless of the position and direction of the drill, scattered radiation doses to the gonad were 1.9- to 4.1-fold higher than those to the eye and thyroid, consistent with the results of previous studies [15, 16]. The reason for these findings may be that the gonad is closer to the X-ray tube for the standard PA C-arm configuration and that the backscatter dose to the gonad is higher than the forward-scatter doses to the eye and thyroid. The annual dose limit to the thyroid set by the National Council on Radiation Protection and Measurements is 300 mSv, but that for the gonad and eye are 50 mSv [24, 25]. Therefore, the surgeon should consider scattered radiation to gonad and eye during intraoperative use of C-arm fluoroscopy. In accordance with this suggestion, the annual use of intraoperative C-arm fluoroscopy should be limited to 8197–11 811 min for the thyroid, 531–1033 min for the gonad and 1742–2577 min for the eye. However, the radiation dose can be reduced using radioprotective equipment; thus, the time limitation for the use of C-arm fluoroscopy can be increased.

Our experiment found that the lowest scattered radiation doses were delivered to the surgeon's radiosensitive organs when the metallic tools were placed beside the pelvis phantom with 90° angulation to the operator phantom. Metallic tools around the pelvis phantom decreased the scattered radiation dose to the eye by 10.8–32.4% and to the thyroid by 14.1–40.4%. However, metallic tools increased the scattered radiation dose to the gonad by 13.9–17.5%, except for the metallic tool beside the pelvis phantom with 90° angulation to the operator phantom (39.6% decrease). These results indicated that the metallic tools around the patient may lower the forward-scatter dose but may increase the backscatter dose. Therefore, when metallic tools are placed around a patient during intraoperative use of C-arm fluoroscopy in standard PA configuration, surgeons should consider the increase in scatter radiation dose to the gonad and wear radioprotective equipment.

In our experiment, the orientation of the metallic tools placed between the patient and the detector did not affect the scattered radiation dose. However, the orientation of the metallic tools beside the patient significantly affected the scattered radiation dose to the surgeon's radiosensitive organs, especially the gonad. Placement of a drill beside the pelvis phantom with 90° angulation to the operator phantom reduced the scattered radiation dose to the radiosensitive organs by 32.4–40.4% compared with reference values and by 21.6–56.2% as compared with the 45° angulation to the operator phantom. We think that the reason for these results is that the scattered radiation from the patient phantom is absorbed by the drill, and the absorbed dose differs according to the orientation of the drill.

Monte Carlo simulation tools such as Monte Carlo N-particle and GEANT are widely used to calculate radiation therapy dose and estimate scattered radiation dose from imaging devices [26]. Several studies have compared the radiation dose between the Monte Carlo calculation and the photoluminescence dosimeter measurement [27–29]. In this study, the scattered radiation doses to surgeon's radiosensitive organs were measured using photoluminescence dosimeters. Monte Carlo simulation tools would be applicable in a comparative study with virtual human phantoms for various medical environment conditions.

In conclusion, this study shows that scattered radiation doses to radiosensitive organs are affected by the location and orientation of metallic tools. Therefore, orthopedic surgeons should consider the effect of metallic tools on the scattered radiation dose during intraoperative use of C-arm fluoroscopy.

CONFLICT OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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