Radiation exposure to the surgeon and patient during a fluoroscopic procedure: how high is the exposure dose? A cadaveric study

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Abstract

Study Design. Using fresh cadavers, real-time dosimeters were used to estimate the radiation exposure dose from C-arm fluoroscopy to surgeons, medical staff, and patients during various procedures.

Objective. To evaluate the radiation exposure dose from C-arm fluoroscopy, which is used to generate real-time images of the human body, under a variety of conditions and in different areas.

Summary of Background Data. Awareness of the harmful effects of long-term low-dose radiation is rising. There are no all-inclusive reports evaluating the radiation exposure dose to medical staff associated with fluoroscopic procedures which can accurately simulate the real clinical situation.

Methods. Seven fresh cadavers were irradiated for 1, 3, and 5 min with C-arm fluoroscopy. The X-ray source was positioned under the table, over the table, and laterally. Radiation exposure doses were measured at different simulated areas such as the center area, and the surgeon's hand or thyroid gland.

Results. There were significant differences in the radiation exposure dose under different conditions and for different irradiated areas. The risk of direct and scatter radiation exposure was the greatest with the lateral position, which increased by more than 200 times and more than 30 times, respectively, compared with that from a position under the table. Direct radiation was attenuated to less than one-hundredth after passing through the body of the cadaver. All radiation exposure doses were positively correlated with total exposure time.

Conclusions. Our study revealed the direct and scatter radiation exposure dose from C-arm fluoroscopy to different areas under a variety of conditions when fluoroscopy is used to generate real-time images of the human body. Our results serve as a guide for medical staff to understand the risk of radiation exposure during each fluoroscopic procedure. Medical staff, especially surgeons, should consider how to protect themselves and reduce radiation exposure by using appropriate shielding.

Key points

- There were significant differences in the radiation exposure dose to different areas under different conditions.
- The lateral position posed the greater risk of both direct and scatter radiation exposure.
- Direct radiation was attenuated to less than one-hundredth after passing through the body of the cadaver.

Mini Abstract

The purpose of this study was to evaluate the radiation exposure dose from C-arm fluoroscopy to different areas under a variety of conditions. There were significant differences in the radiation exposure dose under different conditions. The lateral position posed the greater risk of both direct and scatter radiation exposure.

INTRODUCTION

Most physicians use fluoroscopy to generate real-time images of a patient's body to view the internal anatomy. The fluoroscopic images provide physicians with valuable information that helps determine the appropriate and effective intervention. However, medical staff is exposed to direct and scatter radiation because of the high frequency and long duration of fluoroscopy use and their close proximity to the fluoroscope. The use of C-arm fluoroscopy for spine surgery has rapidly increased because of the increase in minimally invasive procedures.

To our knowledge, though there are some reports about the radiation exposure dose during irradiation of a phantom[1-4], there are no all-inclusive reports that evaluated the radiation exposure dose to medical staff associated with the fluoroscopic procedures used to generate real-time images of the patient's body, in which the real clinical situation was accurately simulated.

The purpose of this study was to evaluate the radiation exposure dose from C-arm fluoroscopy to different areas under a variety of conditions.

MATERIALS AND METHODS

Real-time dosimeters were used to examine the radiation exposure dose from C-arm fluoroscopy for surgeons and patients during various procedures by simulating a common method for intraoperative navigation using fresh cadavers. Seven fresh cadavers (5 males, 2 females) were used for this study. The mean height was 160.1cm (range 140–172 cm) and the mean body weight was 57.9 kg (range 45.5–71 kg). The mean lateral width of the trunk was 29.9 cm (range 23–40 cm) and the mean anteroposterior width of the trunk was 14.6 cm (range 12–22 cm).

This study was approved by the ethics committee of our university hospital.

Instrumentation

All radiation exposures to the body of cadavers were performed using C-arm fluoroscopy (Clearscope1000 (SXT-1000A), Toshiba, Japan); the distance of focus-to-image intensifier was 75 cm. The machines were calibrated every 4 months. An adjustable radiolucent surgical table (MOT-1700, Mizuho, Japan) was used to position the cadavers. The six real-time dosimeters in one setting were mounted onto individual arrays that were fixed to an adjustable jig (Figure 1). The dosimeter can accurately detect exposure ranging from 0 to 9999 milisieverts (mSv). Each radiation dose were recorded in microsieverts (μSv).

C-arm setting

The C-arm fluoroscopy was set to the automatic mode so that technical factors were adjusted automatically to optimize image quality. The C-arm fluoroscopy was tested in three different configurations. 1) The X-ray source of C-arm fluoroscopy was positioned under the radiolucent table. The distance between the X-ray source and the radiolucent table was set to 25 cm when the X-ray source was under the table (Figure 2). 2) The X-ray source of C-arm fluoroscopy was positioned over the radiolucent table. The distance between the X-ray source and the radiolucent table was set to 50 cm when the X-ray source was over the table (Figure 3). 3) The X-ray source of C-arm fluoroscopy was positioned to the side of the cadaver. The distance between the X-ray source and the surface of the cadaver was set to 20 cm when the X-ray source was at the side of the cadaver (Figure 4). The cadavers were then irradiated for 1, 3, and 5 min. The beam was centered on the L3 vertebra. All images of C-arm fluoroscopy were used in a continuous mode without magnification and collimation. The X-ray source technique factors (i.e., kilovolt peak (kV) and milliamperes (mA)) were recorded for each test.

Dosimeter positioning

The six real-time dosimeters in one setting were mounted onto individual arrays as follows.

The X-ray source position: under the table or over the table

When the X-ray source was under or over the radiolucent table (Figure 2, 3), the first dosimeter was placed on the body surface at the center of the image (S1). The second and third dosimeters were placed on the body surface at 5 cm and at 15 cm from the center of the image, respectively (S2, S3). The fourth dosimeter was fixed at 15 cm from the center of the image, in the air at an angle of 20°. The fourth dosimeter was used to simulate the hand of the surgeon (H). The fifth dosimeter was fixed at 50 cm from the center of the image in the air at an angle of 45°. The fifth dosimeter was used to simulate the thyroid gland of the surgeon (T). The sixth dosimeter was fixed beneath the radiolucent table under the cadaver (B). When the X-ray source was under the table, the B dosimeter measured the direct radiation exposure of the patient, and the other five dosimeters measured scatter radiation exposure of the surgeon.

The X-ray source position: lateral position

When the X-ray source was at the side of the cadaver (Figure 1, 4), the first dosimeter was placed on the body surface at the center of the image of the side of the X-ray source (s1). The second dosimeter was placed on the body surface at the center of the image of the intensifier side (contralateral body surface) (s2). The third and the fourth dosimeters were fixed at 15 cm and at

50 cm in the air at an angle of 20° and 45° on the X-ray source side, respectively, which were used to simulate the areas of the hand and thyroid gland of the operator (h1, t1). The fifth and sixth dosimeters were fixed at 15 cm and at 50 cm in the air at an angle of 20° and 45° on the intensifier side (contralateral body surface), respectively. The fifth and the sixth dosimeters were used to simulate the areas of the hand and thyroid gland of the assistant surgeon, respectively (h2, t2). The s1 dosimeter measured the direct radiation exposure of the patient, and the other dosimeters measured scatter radiation exposure of the operator and the assistant surgeon.

The researchers measured and recorded each radiation exposure dose (Figure 5). All personnel involved in this study strictly adhered to safety procedures. All researchers wore a lead apron and neck collar (lead-equivalent thickness of 0.35 mm each) as well as a badge dosimeter and real-time dosimeter on the left chest under the lead apron. All researchers stood at an adequate distance away from the irradiation area.

Statistical analysis

The dose comparison for each part and C-arm position during the examination was analyzed and compared using the unpaired t-test (SPSS software 11.0 J, Tokyo, Japan). P-value < 0.05 indicated statistical significance.

RESULTS

X-ray source positioned under the table

The mean voltage and the mean electric current of C-arm fluoroscopy were 78 kV and 1.6

mA, respectively. The mean radiation exposure for 1, 3, and 5 min of exposure were as follows: the S1 dosimeter showed 145.3±49.8 μSv at 1 min, 451.7±120 μSv at 3 min, and 756±168 μSv at 5 min; the S2 dosimeter showed 24.3±14.4 μSv at 1 min, 67.1±39.6 μSv at 3 min, and 116.7±63.4 μSv at 5 min; the S3 dosimeter showed 6.1±3.8 μSv at 1 min, 18.9±13.2 μSv at 3 min, and 33.4 ±20.1 μSv at 5 min. The H dosimeter showed 12.3±7.9 μSv at 1 min, 27±20 μSv at 3 min, and 61.7±24.9 μSv at 5 min. The T dosimeter showed 2±1.3 μSv at 1 min, 6.7±3 μSv at 3 min, and 12.7±4 μSv at 5 min. The B dosimeter showed 21558.6±5892.7 μSv at 1 min, 67074.3±14776.1 μSv at 3 min, and 109524.3±24284.6 μSv at 5 min (see Table 1). The direct radiation exposure dose at the center of irradiation field was significantly larger than the scatter radiation exposure dose at the peripheral area. The scatter radiation exposure of the H dosimeter was significantly higher than that of the T dosimeter ($p<0.01$).

X-ray source positioned over the table

The mean voltage and the mean electric current of C-arm fluoroscopy were 74.4 kV and 1.5 mA, respectively. The mean radiation exposure for 1, 3 and 5 min of exposure were as follows. The S1 dosimeter showed 17275.4±6127.3 μSv at 1 min, 50457.1±16350.3 μSv at 3 min, and 84222.9±25653.9 μSv at 5 min. The S2 dosimeter showed 114.7±73.8 μSv at 1 min, 386.7±305 μSv at 3 min, and 643.7±576.4 μSv at 5 min. The S3 dosimeter showed 9.9±4.2 μSv at 1 min, 30.1±11.5 μSv at 3 min, and 50.7±19.6 μSv at 5 min. The H dosimeter showed 75.1±34.9 μSv at 1 min, 214.9±93.3 μSv at 3 min, and 360.7±158.6 μSv at 5 min. The T dosimeter showed 14.6±5.6 μSv at 1 min, 43.4±16.1 μSv at 3 min, and 72.4±26.5 μSv at 5 min. The B dosimeter showed 92±17.4 μSv at 1 min, 280.2±41 μSv at 3 min, and 477.3±76 μSv at 5 min (see Table 1). Although the distances of the S3 and H dosimeters from the center of irradiation field were both

15 cm, the scatter radiation exposure of the H dosimeter was significantly higher than that of the S3 dosimeter ($p<0.01$). We found a large difference in scatter radiation exposure between the X-ray source positions. The radiation exposure dose of the S1 dosimeter was very high when the X-ray source position was over the table: it was more than 100 times the radiation exposure dose when the X-ray source was under the table. The scatter radiation exposure doses of S2, H, and T dosimeters when the X-ray source was over the table were significantly higher than those of the dosimeters when the source was under the table (S2 dosimeter, $p=0.015$; H and T dosimeter, $p<0.01$). The scatter radiation exposure of the S3 dosimeter when the X-ray source was over the table was higher than that of the dosimeter when the source was under the table, but the differences were not significant ($p=0.08$). The results of the radiation exposure of the S1 dosimeter compared with that of the B dosimeter indicated that direct radiation was attenuated to less than one-hundredth after passing through the body.

X-ray source positioned laterally

The mean voltage and the mean electric current of C-arm fluoroscopy were 103.9 kV and 2.8 mA, respectively. The mean voltage and the mean electric current of fluoroscopy when the source was positioned laterally were higher than those of fluoroscopy with the source placed under or over the table. The mean radiation exposure after 1, 3, and 5 min of exposure were as follows. The s1 dosimeter showed 35104.3±5362.6 μSv after 1 min, 103285.7±16860.8 μSv after 3 min, and 171542.9±28475 μSv after 5 min. The s2 dosimeter showed 96±50.1 μSv after 1 min, 272.3±135.3 μSv after 3 min, and 450.7±224.2 μSv after 5 min. The h1 dosimeter showed 437±111.3 μSv after 1 min, 1261.4±355.1 μSv after 3 min, and 2104.3±603.6 μSv after 5 min. The h2 dosimeter showed 29.1±16 μSv after 1 min, 85.9±46.9 μSv after 3 min, and 143.9±78.8

μSv after 5 min. The t1 dosimeter showed 92.6±28 μSv after 1 min, 269.1±76.9 μSv after 3 min, and 448.9±125.6 μSv after 5 min. The t2 dosimeter showed 27.7±12.5 μSv after 1 min, 82.7±39.1 μSv after 3 min, and 135±63.9 μSv after 5 min (see Table 2). The direct radiation exposure dose of the s1 dosimeter was very large; only 1 min of radiation exposure resulted in a dose exceeding 35 mSv. The scatter radiation exposure dose of the h1 dosimeter that was meant to provide an estimate of the dose received by the operator's hand was high, and only 3 min of radiation exposure resulted in a dose exceeding 1000 μSv. The scatter radiation exposure dose of the h1 dosimeter was significantly higher than that of the t1 dosimeter ($p<0.01$). The scatter radiation exposure dose of the h1 dosimeter was significantly higher than that of the h2 dosimeter ($p<0.01$). Similarly, the scatter radiation exposure dose of the t1 dosimeter was significantly higher than that of the t2 dosimeter ($p<0.01$).

There was significant positive correlation between the relationship of irradiation time and radiation exposure dose of direct radiation (s1 dosimeter) and scatter radiation (h1, t1 dosimeter) for C-arm fluoroscopy in the lateral position (Figure 6).

The researchers who measured the exposure doses received radiation exposure that was less than the minimum reportable dose in all their badge dosimeters that were protected at the left chest. Similarly, the radiation exposure dose was within 3 μSv each time in all of the real-time dosimeters that were protected at the left chest.

DISCUSSION

In our study, we systematically quantified radiation exposure sustained by the patient and surgeon during use of C-arm fluoroscopy to image a body part with the X-ray source in different positions. The main results in this experiment are 1) the higher direct and scatter radiation exposure dose resulted from C-arm fluoroscopy in the lateral position compared with those from fluoroscopy with the source under the table or over the table; 2) attenuation of the dose of direct radiation to less than one-hundredth after passing through the body; and 3) variation in the scatter radiation exposure doses with differences in the incident angle of the X-ray beam passing through the body, although the distance from the center of irradiation field is the same.

More X-ray beams are needed to penetrate a thicker section of the body to maintain image quality. The highest dose occurs when imaging the thickest part of the patient, which is why a lateral image results in more radiation than an A-P image. This is especially pertinent to the spinal surgeon. Jones et al. revealed that the dose in spine procedures is 10 to 12 times greater than those during non-spine procedures[4].

It stands to reason that the radiation exposure dose increases as the irradiation time is increased. In this study, the radiation exposure dose measured at all sites was positively correlated with the total exposure time at every position of the X-ray source. The surgeon should use single-shot fluoroscopy and pulsed mode fluoroscopy[5] and should plan the procedure sufficiently to minimize the time of exposure.

In this study, we revealed that there was much scatter radiation exposure to the hand and thyroid gland of the surgeon when the X-ray source was positioned over the table and laterally (Figure 7). Many studies have demonstrated that the use of protective equipment including use of a lead apron, thyroid shield and lead gloves can decrease the amount of exposure[3, 6, 7], but it is questionable whether their use is sufficient. We also found that the body of the cadaver itself had a significant attenuation effect (Table 1, S1 and B) (Table 2, s1 and s2). The surgeon should perform the fluoroscopic procedure so that the body of the patient is between the hand and the X-ray source. Thus, if the surgeon's hand strays into the main X-ray irradiation area, the radiation would be substantially attenuated by the body of the patient.

Some studies demonstrated that the greater the distance the surgeon is from the X-ray source, the lower the radiation exposure to the surgeon[8, 9]. We revealed concrete real exposure doses for the surgeon's hand and thyroid gland depending on the position of the X-ray source. In our study, the scatter exposure doses for the surgeon and assistant surgeon were very different from when the X-ray source is positioned laterally. Surgeons should work on the image intensifier side of the patient rather than on the X-ray source side, and they should move their hands as far away from the irradiated area during fluoroscopic screening.

This study provided initial radiation exposure data accurately during use of C-arm fluoroscopy to image the human body in a simulated surgical procedure with the X-ray source in different positions. The results of the study serve a guide to the amount of radiation exposure in each fluoroscopic procedure. In conclusion, this study has shown that the radiation exposure dose changes significantly with the position of the X-ray source, and it was especially high when the source was in the lateral position. The surgeon should evaluate the exposure dose with every procedure, and protect their hand and thyroid gland using appropriate shielding.

Conflict of interest

All authors confirm that there are no conflicts of interest with people or organizations that could bias the nature of this report.

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Table 1. Average radiation exposure dose (X-ray source, under the table and over the table)

Dose		μSv						over/under ratio
		under			over			
		1 min	3 min	5 min	1 min	3 min	5 min	5 min
S1	center of irradiation field	145.3±49.8	451.7±120	756±168	17275.4 ±6127.3	50457.1 ±16350.3	84222.9 ±25653.9	111.4
S2	5 cm on the body surface	24.3±14.4	67.1±39.6	116.7±63.4	114.7 ±73.8	386.7 ±305	643.7 ±576.4	5.52
S3	15 cm on the body surface	6.1±3.8	18.9±13.2	33.4±20.1	9.9±4.2	30.1±11.5	50.7 ±19.6 †	1.52
H	15 cm in the air	12.3±7.9	27±20	61.7±24.9 *	75.1±34.9	214.9 ±93.3	360.7 ±158.6 †	5.85
T	50 cm in the air	2±1.3	6.7±3	12.7±4 *	14.6±5.6	43.4±16.1	72.4±26.5	5.7
B	beneath the radiolucent table	21558.6 ±5892.7	67074.3 ±14776.1	109524.3 ±24284.6	92±17.4	280.3±41	477.3±76.0	0.004

* $p<0.01$, † $p<0.01$

Table 2. Average of radiation exposure dose (X-ray source, lateral)

Dose		μSv lateral		
		1 min	3 min	5 min
s1	center of irradiation field (X-ray source side)	35104.3±5362.6	103285.7±16860.8	171542.9±28475 *
s2	center of irradiation field (intensifier side)	96±50.1	272.3±135.3	450.7±224.2 *
h1	15 cm in the air (X-ray source side)	437±111.3	1261.4±355.1	2104.3±603.6 † **
h2	15 cm in the air (intensifier side)	29.1±16	85.9±46.9	143.9±78.8 †
t1	50 cm in the air (X-ray source side)	92.6±28	269.1±76.9	448.9±125.6 ‡ **
t2	50 cm in the air (intensifier side)	27.7±12.5	82.7±39.1	135±63.9 ‡

* $p<0.01$, † $p<0.01$, ** $p<0.01$, ‡ $p<0.01$

Figure legends

Figure 1. Six real-time dosimeters (arrows) were mounted onto individual arrays that were fixed to an adjustable jig when the X-ray source was positioned on the side of the cadaver.

Figure 2. The position of the X-ray source and dosimeters during testing. The X-ray source is under the radiolucent table.

Figure 3. The position of the X-ray source and dosimeters during testing. The X-ray source is above the radiolucent table.

Figure 4. The position of the X-ray source and dosimeters during testing. The X-ray source is at the side of the cadaver.

Figure 5. The image of the lumbar vertebra and dosimeters when the X-ray source is under the table (small arrow indicates dosimeter S1, the big arrow indicates dosimeter B).

Table 1. Average of radiation exposure dose (comparison between under the table and over the table).
* $p<0.01$, † $p<0.01$

Table 2. Average of radiation exposure dose (X-ray source, lateral)
* $p<0.01$, † $p<0.01$, ** $p<0.01$, ‡ $p<0.01$

Figure 6. Positive correlation between irradiated time and radiation dose of direct radiation and scatter radiation (X-ray source, lateral).

Figure 7. Schematic view of these findings indicating the extent of the direct and scatter radiation when the source is over the table and in the lateral position.

Figures

Figure 1.

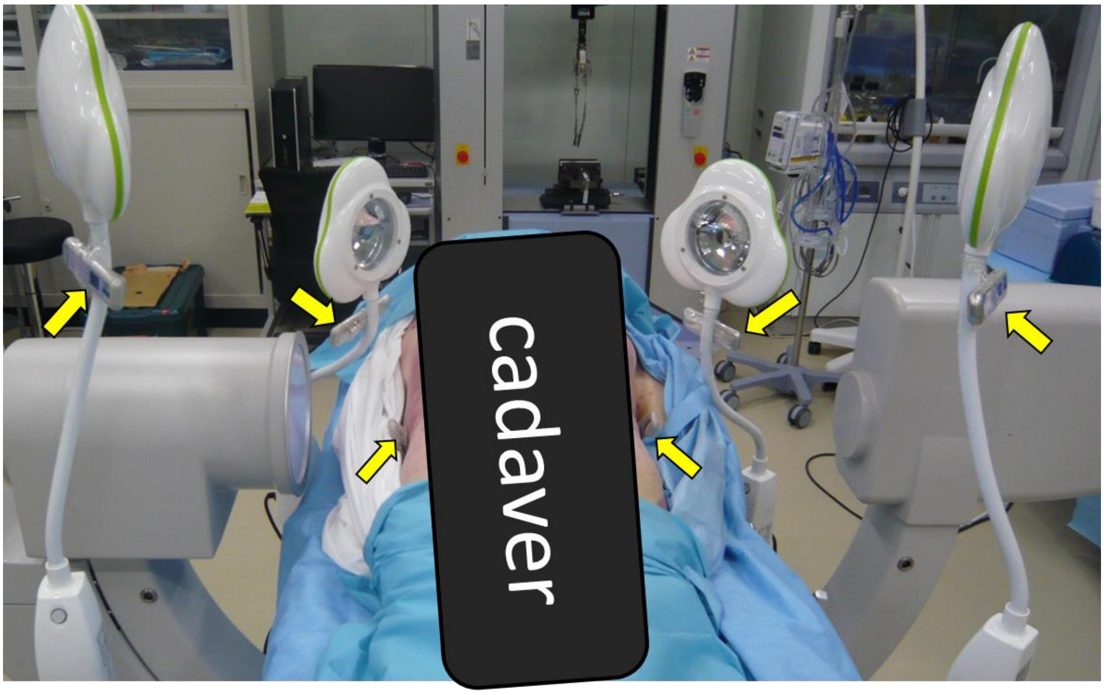


Figure 2.

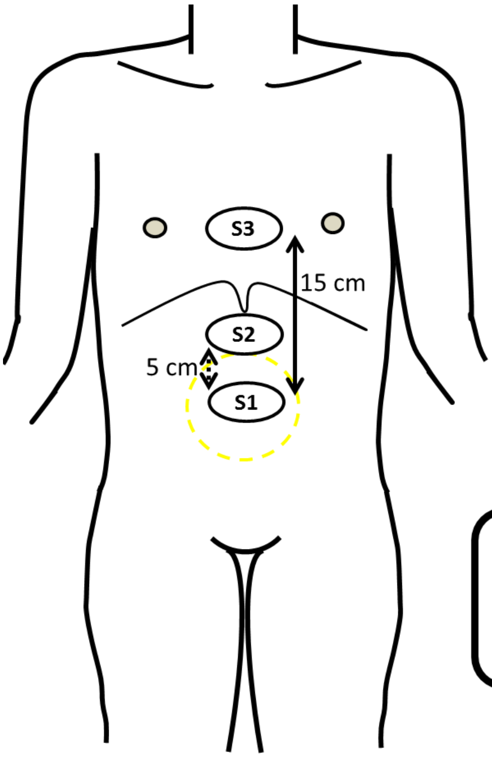


Figure 2a

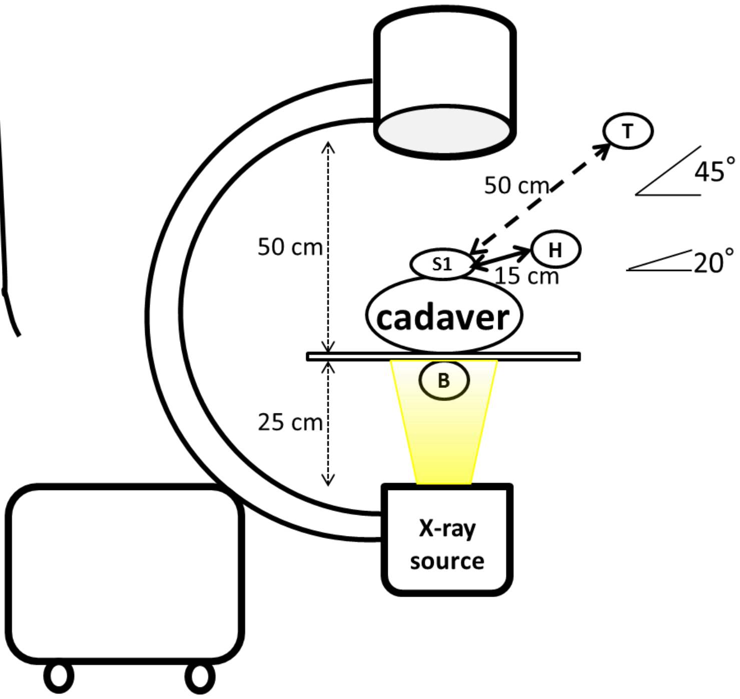
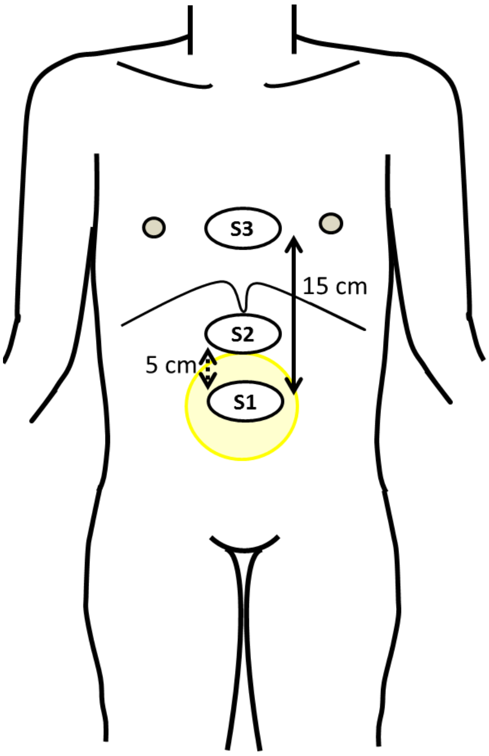


Figure 2b

Figure 3.



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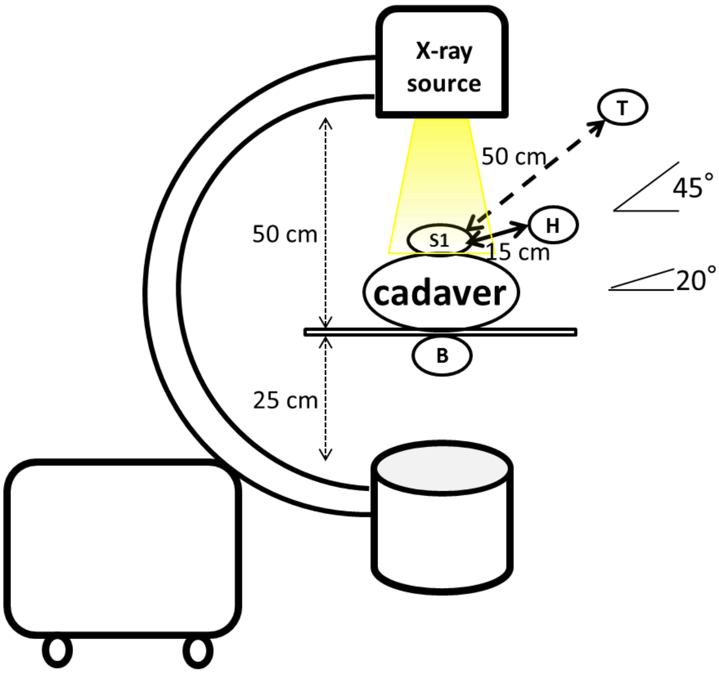


Figure 3b

Figure 4.

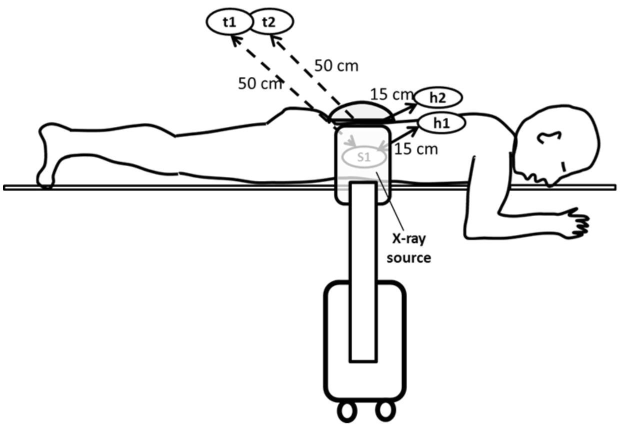


Figure 4a

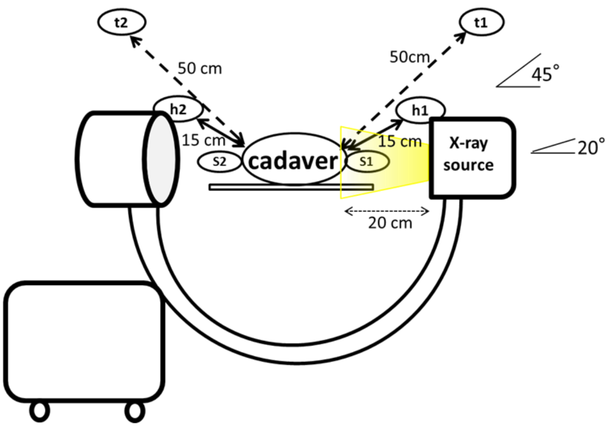


Figure 4b

Figure 5.

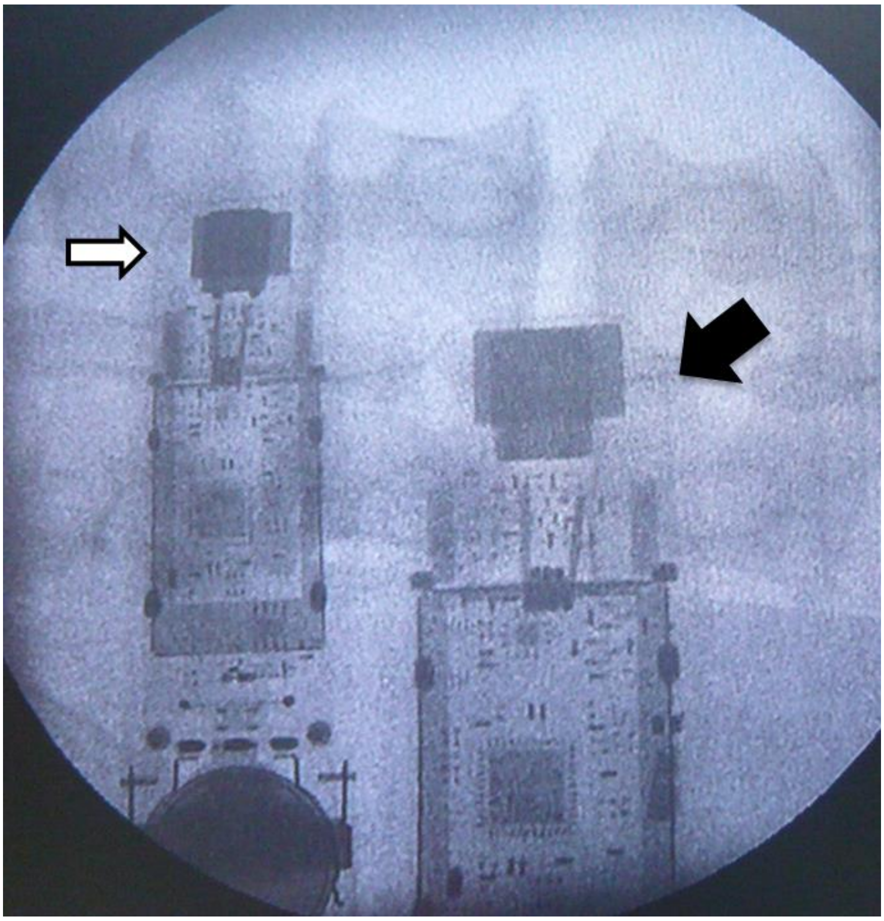
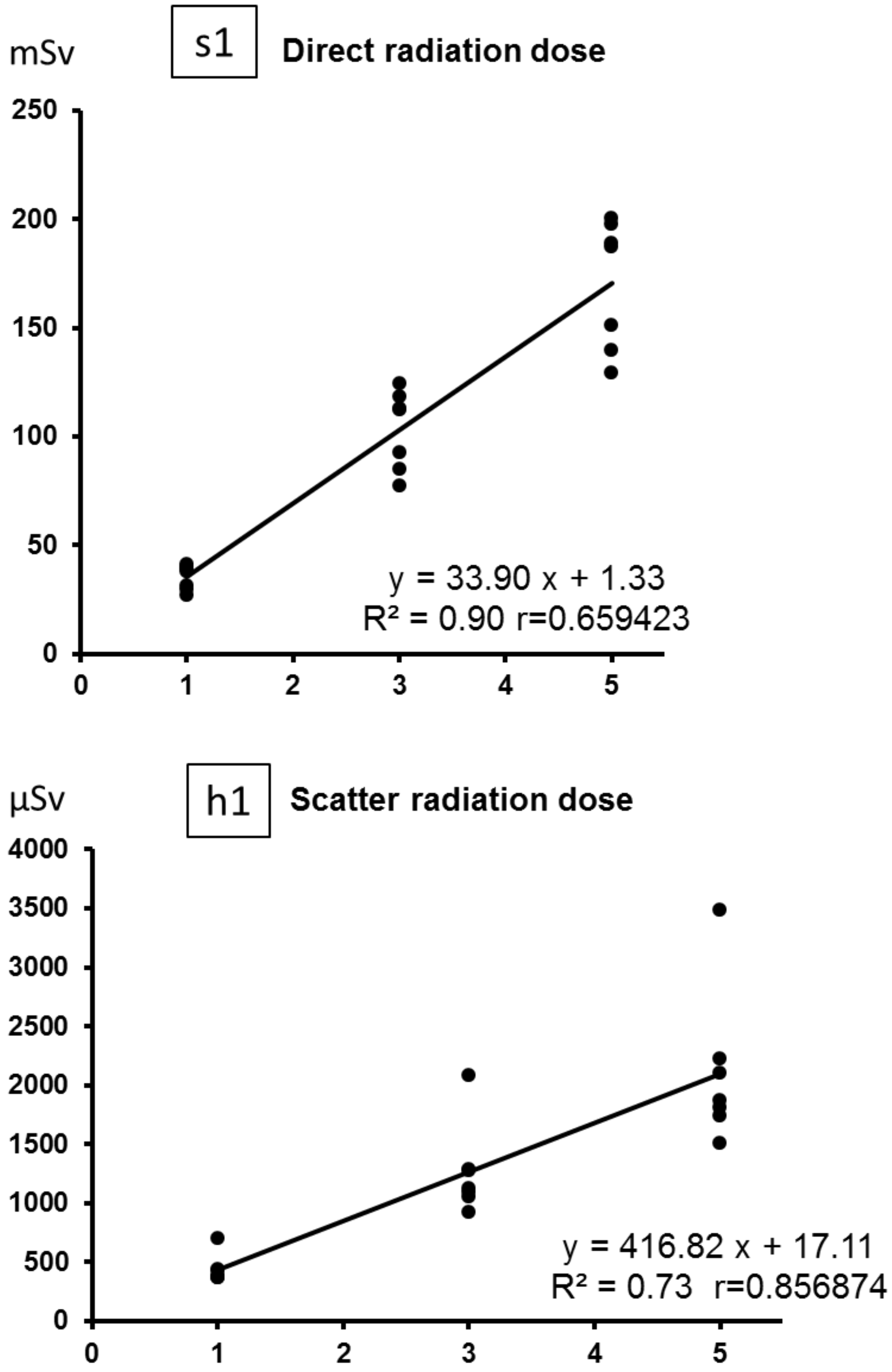


Figure 6.



mSv
s1
Direct radiation dose
250
200
150
100
50
0
0
1
2
3
4
5
y = 33.90 x + 1.33
R² = 0.90 r=0.659423
µSv
h1
Scatter radiation dose
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
y = 416.82 x + 17.11
R² = 0.73 r=0.856874

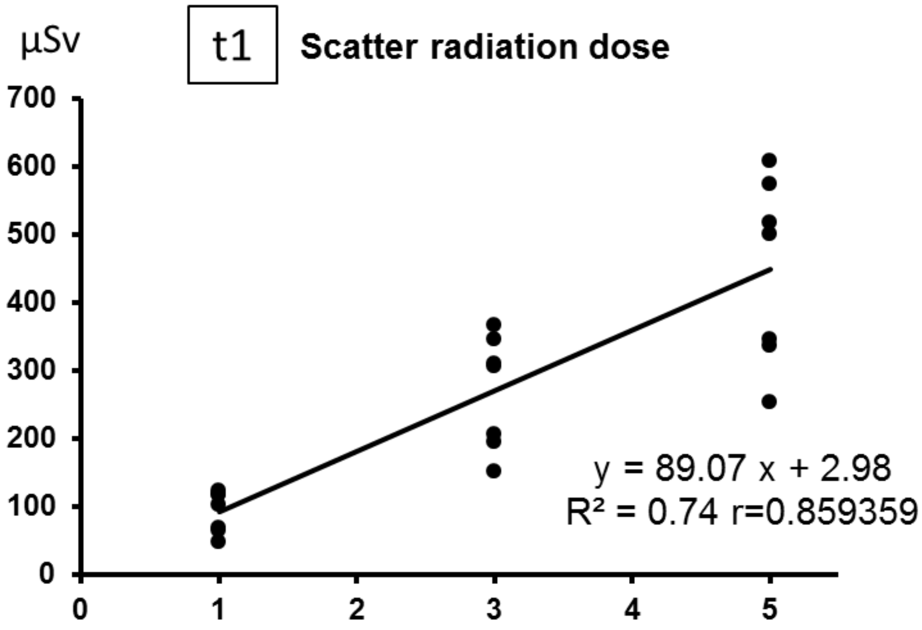
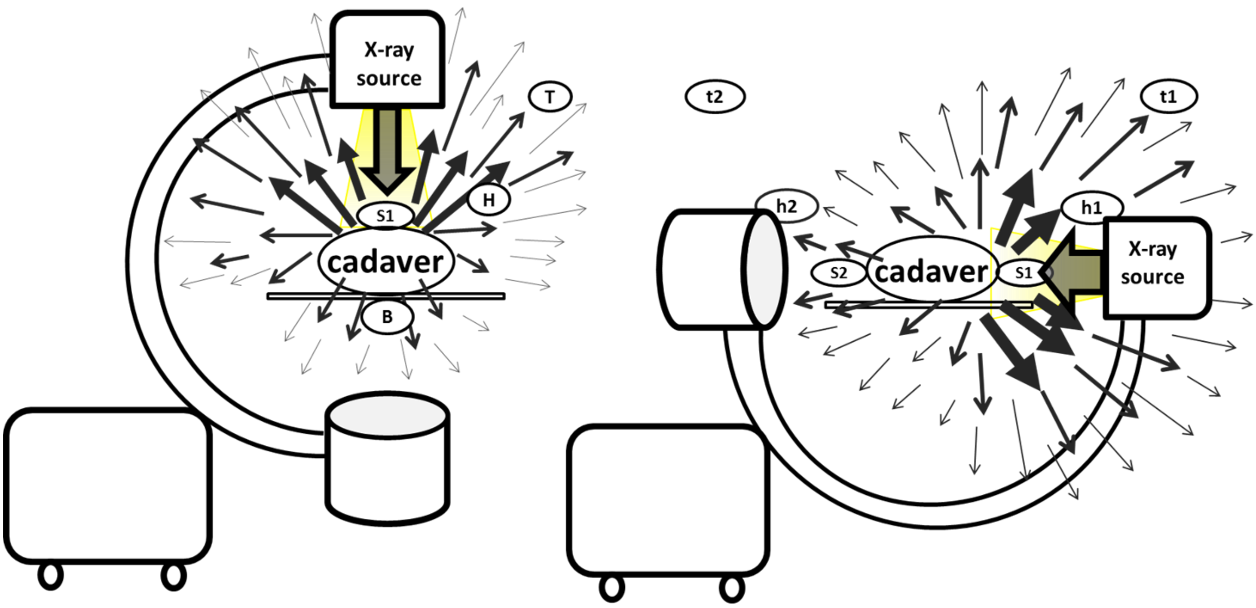

μSv
t1
Scatter radiation dose
700
600
500
400
300
200
100
0
0
1
2
3
4
5
y = 89.07 x + 2.98
R² = 0.74 r=0.859359

Figure 7.



X-ray source
T
H
S1
cadaver
B
t2
t1
h2
h1
S2
cadaver
S1
X-ray source