Effective Dose during Abdominal Three-dimensional Imaging with a Flat-Panel Detector Angiography System[1]

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The purpose of this study was to measure the effective dose during abdominal three-dimensional imaging obtained with an angiography unit with a digital flat-panel system on a phantom and to determine dose-area product (DAP)-to–effective dose conversion factors. DAPs and effective doses were evaluated for 163-cm-tall human-shaped phantoms with estimated body weights of 54, 64, and 77 kg, and the effective doses were 2.1, 3.2, and 4.2 mSv, respectively. The DAP-to–effective dose conversion factors were 0.28–0.29 mSv · Gy^{-1} · cm^{-2}. In conclusion, the DAPs were useful for estimating the effective dose during abdominal three-dimensional angiographic imaging.

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Radiology

Minimally invasive imaging-guided vascular interventions have recently become widespread and have been used successfully in the treatment of various diseases. These procedures sometimes require prolonged radiation exposure times with an increased risk of stochastic effect. Therefore, it is important to estimate a patient's effective dose, which is of particular value in estimating the stochastic effect. The dose-area product (DAP) is often used to assess the effective dose during procedures performed with fluoroscopic guidance (1–7). DAP-to–effective dose conversion factors (CFs) have been evaluated for some procedures in the literature (8,9).

Recently, three-dimensional (3D) imaging by using an angiography system with a larger flat-panel detector has been developed. Three-dimensional vascular and cross-sectional images have begun to be used for abdominal vascular intervention, too (10,11). However, the patient's effective dose during the 3D imaging has not been adequately assessed in the literature. Existing CFs do not cover the dose received during 3D imaging. The purpose of our study is to measure the effective dose during abdominal 3D imaging with a phantom and to determine the CF.

Materials and Methods

Human-shaped Phantom

To assess the effect of object thickness on the effective dose, we used three sizes (small, medium, and large) of a human-shaped phantom. The small phantom was a 163-cm-tall 54-kg female phantom (Rando phantom; Phantom Laboratories, Salem, NY). For our study, we regarded the phantoms as hermaphrodite phantoms. We made the other phantoms by wrapping a 2.1 kg (medium phantom) or 4.2 kg (large phantom) polyethylene attachment around the upper abdomen of the small phantom. The attachment was 25-cm wide in the craniocaudal direction. With the attachments, the waist circumferences of the medium and large phantoms were 83 and 93 cm, respectively. Cornier et al (12) evaluated the relationship between waist circumference and body mass index. On the basis of their data, the estimated body mass indexes of the medium and large phantoms corresponded to 23.8 and 29.3 kg/m^2, respectively, which resulted in calculated body weights of 64 and 77 kg, respectively.

Angiography Unit and 3D Imaging

We used an angiography unit with a digital flat-panel detector system (Innova 4100; GE Medical Systems, Milwaukee, Wis). This system is available for 3D imaging and has four fields of view (FOVs): 40, 32, 20, and 16 cm. The 40-cm FOV was used in our assessment, and the FOV at the axis of rotation was 24 cm. The removable additional filter used was 0.3 mm of copper, and the total filtration without the removable additional filter was equivalent to 3.5 mm of aluminum. The distance from the source to the axis of rotation was 71 cm, and the distance from the source to the image plane was 118 cm. The field size at the interventional reference point was 24 cm in diameter. The rotation range was 194°, and the duration of a rotation was 5, 10, or 20 seconds (148, 293, or 587 projections, respectively). At our institution, a 5-second acquisition is most frequently used.

Three-dimensional imaging with a 5-second acquisition was performed 10 times for the human-shaped phantoms to reduce the dispersion of response among dosimeters. As will be described later, the dispersion of response among the dosimeters decreases as the exposure dose increases. In the direction of the z-axis, we set the center of the vertebral body of the first lumbar vertebra at the center of the exposure field, and the center of rotation was located at the anterior edge of the phantom's first lumbar vertebra. All exposed parts of the phantom surface were covered with the polyethylene attachment. The tube voltage, tube current–time product, pulse width, removable additional filter, and size of the focal spot were determined automatically (Table 1). The number of pulses was equal to that of the projections. As for tube current, the tube current–time product was only available for the last projection. In this angiography system, the DAP value was calculated automatically without a DAP meter. The DAP calculation had been adjusted at the time of regular maintenance. The angiographic data in Table 1 represent the normal clinical settings for this system.

Direct Dose Measurement

Direct measurement of organ doses was performed by using the three sizes of the human-shaped phantom. The Rando phantom had holes of 5-mm diameter at 3-cm intervals for the insertion of dosimeters. We measured the doses at a total of 180 points by using a radiophotoluminescent glass dosimeter (RPLGD) (GD-351; Asahi Techno Glass, Shizuoka, Japan) and determined the doses of 25 organs (Tables 2, 3) on the basis of the methods of previous reports (13,14). The location of the other organs was specified on the phantom by a radiologist.

Advances in Knowledge

- Dose-area product (DAP)-to–effective dose conversion factors were 0.3 mSv · Gy^{-1} · cm^{-2} for abdominal three-dimensional angiographic imaging.
- DAP-to–effective dose conversion factors tended to decrease slightly as phantom weight and height increased.

Implication for Patient Care

- DAPs are useful for estimating the effective dose during three-dimensional imaging.

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Abbreviations:
CF = conversion factor
DAP = dose-area product
FOV = field of view
3D = three-dimensional

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Guarantor of integrity of entire study, S.S.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; literature research, all authors; experimental studies, all authors; statistical analysis, S.S., S.F.; and manuscript editing, S.S., S.F.

The RPLGD has a holder with an energy compensation filter of 0.75 mm of tin. Before the exposure, the glass elements of the RPLGD were annealed for 1 hour at 400°C and then slowly cooled to room temperature. After the exposure, a preheating process was performed for 30 minutes at 70°C. Then a fully automatic system (FGD-1000; Asahi Techno Glass) was used for the readout. Calibration was performed by using a standard glass irradiated with cesium 137 gamma ray energy (0.662 MeV) of 6 mGy. According to the data provided by the manufacturer, the dispersion of response among the dosimeters decreases as the exposure dose in-

Table 1

Angiographic Data for Each Phantom Size

Parameter	Small	Medium	Large
Height (cm)	163	163	163
Weight (kg)	54	64	77
Inherent filtration (mm of aluminum)	3.5	3.5	3.5
Additional filtration (mm of copper)	0.3	0.3	0.3
Pulse width (msec)	7	7	7
Focal spot (mm)	1	1	1
Tube voltage (kVp)*	80.0 ± 0.1	83.9 ± 0.1	85.0 ± 0.0
Tube current–time product (mAs)†	2.36 ± 0.03	3.00 ± 0.02	3.96 ± 0.05
Estimated patient thickness (cm)‡	19.0 ± 0.2	21.9 ± 0.2	24.1 ± 0.1
DAP (Gy · cm^2)*	7.3 ± 0.3	11.0 ± 0.6	15.3 ± 0.7

* Data are mean ± standard deviation.

† Data are mean per pulse ± standard deviation.

‡ Data are mean ± standard deviation; automatically calculated by the angiographic unit.

Table 2

Organ and Tissue Doses for Each Phantom Size

Organ or Tissue Dose	No. of Measurement Points	Mean Absorbed Dose (mGy)						Difference between Methods (%)‡		
		Direct Measurement*			Monte Carlo Technique†					
		Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
Ovaries	2	0.28 (0.01)	0.44 (0.04)	0.69 (0.06)	0.29 (0.03)	0.57 (0.05)	0.77 (0.07)	4 (3)	30 (12)	12 (9)
Testes	2	0.020 (0.002)	0.031 (0.005)	0.048 (0.009)	0.0061 (0.0023)	0.013 (0.004)	0.012 (0.005)	−70 (4)	−58 (7)	−75 (5)
Active bone marrow	21	1.5 (0.1)	2.2 (0.2)	3.1 (0.3)	1.8 (0)	2.6 (0)	3.3 (0)	20 (12)	18 (13)	6 (12)
Lower large intestine	5	0.64 (0.03)	0.89 (0.10)	1.3 (0.1)	0.40 (0.01)	0.59 (0.01)	0.70 (0.02)	−38 (2)	−34 (8)	−46 (4)
Lungs	18	2.5 (0.1)	4.1 (0.3)	5.5 (0.3)	3.1 (0)	4.4 (0)	5.4 (0)	24 (6)	7 (8)	−2 (5)
Stomach	6	4.5 (0.4)	6.7 (1.0)	8.0 (0.4)	4.9 (0)	7.1 (0.1)	7.5 (0.1)	9 (9)	6 (17)	−6 (5)
Urinary bladder	2	0.16 (0.01)	0.25 (0.02)	0.39 (0.02)	0.08 (0.01)	0.13 (0.01)	0.18 (0.01)	−48 (2)	−48 (5)	−54 (2)
Breasts	2	2.5 (0.2)	4.7 (0.3)	6.6 (0.6)	0.49 (0.01)	0.68 (0.01)	0.72 (0.01)	−80 (1)	−86 (1)	−89 (1)
Liver	9	4.8 (0.1)	7.3 (0.4)	9.5 (0.8)	6.8 (0)	9.4 (0)	11.9 (0)	42 (2)	29 (8)	25 (12)
Esophagus	4	1.9 (0.1)	3.0 (0.3)	4.2 (0.4)	1.4 (0)	2.1 (0)	2.5 (0.1)	−26 (3)	−30 (8)	−40 (6)
Thyroid	2	0.093 (0.008)	0.17 (0.02)	0.24 (0.02)	0.032 (0.006)	0.05 (0.01)	0.062 (0.013)	−66 (3)	−71 (3)	−74 (2)
Skin	12	1.0 (0.1)	1.5 (0.2)	2.0 (0.2)	1.3 (0)	2.0 (0)	2.5 (0)	30 (9)	33 (14)	25 (16)
Skeleton	24	1.3 (0.1)	1.9 (0.2)	2.7 (0.3)	2.6 (0)	3.6 (0)	4.7 (0)	100 (19)	89 (21)	74 (21)
Adrenals	4	6.6 (0.3)	10.0 (0.6)	13.4 (0.9)	10.5 (0.2)	14.6 (0.2)	19.7 (0.3)	59 (7)	46 (9)	47 (11)
Brain	3	0.011 (0.001)	0.018 (0.001)	0.027 (0.001)	0	0	0	−100 (0)	−100 (0)	100 (0)
Upper large intestine	3	3.5 (0.3)	4.7 (0.4)	6.1 (0.6)	2.6 (0)	3.5 (0)	4.1 (0)	−26 (7)	−26 (6)	−33 (7)
Small intestine	12	2.5 (0.1)	3.4 (0.4)	4.6 (0.5)	2.0 (0)	2.9 (0)	3.4 (0)	−20 (4)	−15 (10)	−26 (9)
Kidneys	6	8.2 (0.7)	11.7 (1.4)	15.8 (1.8)	13.9 (0.1)	19.5 (0.1)	26.7 (0.1)	70 (15)	67 (21)	69 (20)
Muscle	28	2.2 (0.2)	3.1 (0.3)	4.2 (0.5)	1.5 (0)	2.1 (0)	2.7 (0)	−32 (6)	−32 (6)	−36 (8)
Pancreas	2	5.1 (0.2)	7.6 (0.6)	9.6 (0.3)	6.4 (0.1)	8.8 (0.1)	10.6 (0.1)	25 (4)	16 (9)	10 (3)
Spleen	4	8.7 (0.7)	12.5 (1.5)	17.1 (2.0)	11.0 (0.1)	15.3 (0.1)	18.8 (0.1)	26 (11)	22 (16)	10 (14)
Thymus	2	0.48 (0.01)	0.84 (0.02)	1.2 (0)	0.36 (0.02)	0.56 (0.03)	0.67 (0.05)	−25 (1)	−33 (2)	−44 (2)
Uterus	2	0.23 (0.01)	0.35 (0.03)	0.53 (0.03)	0.31 (0.01)	0.47 (0.02)	0.65 (0.02)	35 (5)	34 (10)	23 (7)
Heart§	3	3.6 (0.1)	5.7 (0.3)	7.8 (0.4)	2.8 (0)	3.9 (0)	4.7 (0)	−22 (2)	−32 (3)	−40 (3)
Gallbladder§	2	5.0 (0.5)	7.0 (0.6)	9.2 (0.8)	4.4 (0.1)	5.9 (0.1)	7.0 (0.1)	−12 (9)	−16 (8)	−24 (7)

* Numbers in parentheses are standard deviations.

† Estimated error was calculated by the program. Numbers in parentheses are standard errors.

‡ Difference = $(D_{Mon} - D_{Dir})/D_{Dir}$, where D_{Mon} is mean dose by Monte Carlo technique and D_{Dir} is dose by direct measurement. Mean differences were calculated from the three direct measurements. Data in parentheses are standard deviations.

§ Not included in effective dose calculation.

creases (coefficient of variation is 8% at 0.03 mGy, 3% at 0.1 mGy, and ≤ 2% at 1 mGy or more). To reduce the dispersion of response among the dosimeters, the 3D acquisition was performed 10 times. To determine the dose of each measurement point for one acquisition of 3D images, we subtracted the background from the reading value and divided it by the number of exposures (ie, 10). Effective doses were calculated by using the definition the International Commission on Radiological Protection reported in 1995 (15). We also calculated effective doses normalized to unit DAP (ie, CF). To estimate the uncertainty in these dose assessments, we repeated the direct measurements of the organ doses for all the three phantom sizes three times.

Dose Measurement with Monte Carlo Technique

Organ doses and effective doses were also calculated by using the Monte Carlo technique for the three human-shaped phantoms. Software (PCXMC; Radiation and Nuclear Safety Authority, Helsinki, Finland) was used for the calculation of the organ doses (16). The anatomic data were determined on the basis of a mathematic phantom that represented an average adult patient. This phantom was specified by Cristy (17) and modified by the methods of Jones and Wall (18) and Zankl et al (19). We modified the size of the mathematic phantom by changing the weight and height to those of the three human-shaped phantoms.

For simplification, we evaluated the doses of the 25 organs in 13 projections at 15° intervals (right lateral, right anterior oblique [15°, 30°, 45°, 60°, 75°], posteroanterior, left anterior oblique [75°, 60°, 45°, 30°, 15°], and left lateral views) with this method, although data from 148 projections are used for actual acquisition of 3D images. We assumed that the angiographic parameters were equal in each projection in this assessment. To calculate the organ doses for each projection, the radiographic projection data (projection angle, position, field size, DAP, tube voltage, and total filtration) in Table 1 were entered into the program, and a Monte Carlo technique was used to track the energy deposition of 360 000 x-ray photons throughout the phantom. Each reported organ dose was calculated by summing the doses in the 13 projections. We calculated effective doses and CFs by using the definition the International Commission on Radiological Protection established in 1995 (15).

Relationship between Height and CF

By using the Monte Carlo technique, we also calculated the CFs for two other heights of the mathematic phantom. One was 155 cm tall and weighed 61 kg, and the other was 174 cm tall and weighted 68 kg. The calculated patient thickness and width of these two mathematic phantoms were equal to those of the medium phantom (19.6-cm thick and 33.7-cm wide). By using the angiographic data for the medium phantom in Table 1, we calculated the CFs for the two heights of phantom and compared the CFs with those for the medium phantom.

Results

The doses to organs in the upper abdomen were larger than those to the other organs (Table 2). Among the upper abdominal organs, the doses to the dorsal organs (eg, kidneys and adrenal glands) were larger than those to the ventral organs (eg, liver and stomach).

The DAP, organ doses, and effective dose increased as phantom size increased. The DAP (15.3 Gy · cm^2) and the effective dose (4.2 mSv) for the large phantom were double those for the small phantom (DAP, 7.3 Gy · cm^2; effective dose, 2.1 mSv). CFs were 0.28–0.29 mSv · Gy^{-1} · cm^{-2}, and the CF decreased as phantom size increased.

The organ doses and the effective doses calculated with the Monte Carlo technique corresponded well to those obtained by direct measurement. The former tended to be slightly larger than the latter. The differences between the effective doses obtained by using the two methods were within 10% of each other.

CFs calculated by using the Monte Carlo technique for 155-, 163-, and 174-cm-tall mathematic phantoms were 0.31 mSv · Gy^{-1} · cm^{-2}, 0.30 mSv · Gy^{-1} · cm^{-2}, and 0.28 mSv · Gy^{-1} · cm^{-2}, respectively, and the CF decreased as the phantom height increased.

Table 3

Dose Data for Each Phantom Size

Parameter	Mean Absorbed Dose: Direct Measurement* Small	Direct Measurement* Medium	Direct Measurement* Large	Monte Carlo Technique† Small	Monte Carlo Technique† Medium	Monte Carlo Technique† Large	Difference between Methods (%)‡ Small	Difference between Methods (%)‡ Medium	Difference between Methods (%)‡ Large
Effective dose (mSv)	2.1 (0.1)	3.2 (0.3)	4.2 (0.3)	2.3 (0)	3.3 (0)	4.0 (0)	10 (6)	3 (10)	−5 (7)
DAP (Gy · cm^2)	7.3 (0.3)	11.0 (0.6)	15.3 (0.7)	7.3§	11.0§	15.3§	Not applicable	Not applicable	Not applicable
Effective dose/DAP (mSv · Gy^{-1} · cm^{-2})	0.29 (0.01)	0.29 (0.01)	0.28 (0.01)	0.32 (0)	0.30 (0)	0.26 (0)	10 (2)	3 (5)	−7 (3)

* Numbers in parentheses are standard deviations.

† Estimated error was calculated by the program. Numbers in parentheses are standard errors.

‡ Difference = $(D_{Mon} - D_{Dir})/D_{Dir}$, where D_{Mon} is mean dose by Monte Carlo technique and D_{Dir} is dose by direct measurement. Mean differences were calculated from the three direct measurements. Data in parentheses are standard deviations.

§ Average of the direct measurements.

Discussion

Three-dimensional imaging with an angiography system has mainly been used for head and neck vascular intervention (20,21). It is useful for understanding the anatomic relationship, determining the feeding arteries of tumors, and identifying the distribution of drugs injected through a catheter. Recently, 3D imaging for abdominal vascular intervention has been enabled by large flat-panel detectors (10,11). However, the patient's effective dose during this technique has not been adequately addressed in the literature.

The effective dose during 3D imaging with an angiography system was 2.1 mSv for the small phantom. This dose is less than that received during abdominal computed tomography (CT); Ware et al (22) reported that the mean effective dose was 3.9 mSv for adults undergoing CT with a section thickness of about 7 mm and an average number of sections of 31.5. However, the DAP, organ doses, and effective dose during 3D imaging increased as phantom size increased, since the tube voltage and current during imaging were automatically controlled on the basis of the object thickness. It should be considered that the patient's effective dose during 3D imaging accumulates faster in larger patients. The DAP and effective dose are affected by acquisition time, too. They will increase linearly as the acquisition time increases from 5 to 20 seconds. Thus, the effective dose for a 20-second acquisition would be four times as high as that for a 5-second acquisition.

For some fluoroscopic procedures, CFs have been reported in the literature (8,9). Three-dimensional imaging with an angiography system is calculated from multiple projection data by using Feldkamp algorithms (23). Therefore, the CFs for the whole 3D imaging session can be calculated by averaging the CFs obtained for each projection with the Monte Carlo technique. In our study, the CFs calculated by using the Monte Carlo technique were 0.26–0.32 $mSv \cdot Gy^{-1} \cdot cm^{-2}$, and they corresponded well to those obtained with direct measurement (0.28–0.29 $mSv \cdot Gy^{-1} \cdot cm^{-2}$).

The organ doses and the effective doses calculated by using the Monte Carlo technique tended to be slightly higher than those obtained by using direct measurement. The physical relationship of organs and the distribution of fat tissue must be different between the mathematic phantom and the Rando phantom, which would contribute to the difference in organ doses between the two methods. In the mathematic phantom used for the Monte Carlo technique, a cylinder represented the trunk (17), and there was no physiologic curve of the vertebral column. Therefore, the dorsal organs (eg, kidneys and adrenal glands) were probably situated more posteriorly in the mathematic phantom, which would result in larger doses. The trunk lengths of the phantoms may also differ, and that could affect the dose to organs distant from the exposure field (eg, brain, thyroid, urinary bladder, and testes). The restricted number of measurement points in the direct measurement method also affected the organ doses. For example, there was one measurement point for each breast, and it was included in the exposure field. However, some parts of the breasts existed outside of the exposure field. This resulted in potential overestimation of the breast dose by direct measurement. The restricted number of measurement points probably affected the calculated doses to extensive organs (eg, skeleton and intestine), too. However, the differences between the effective doses calculated with the two methods were within 10% and are not noteworthy in practical dose evaluation.

In our study, the CFs were about 0.3 $mSv \cdot Gy^{-1} \cdot cm^{-2}$ for 3D abdominal imaging, though phantom weight and height slightly affected the CFs. It is useful for estimating patients' effective doses during 3D imaging, since DAPs are available for many of the newer angiography units. The effective doses for fluoroscopy and digital subtraction angiography acquisition can be calculated by using CFs, too. Therefore, the total effective dose during an abdominal vascular intervention with 3D imaging can be evaluated on the basis of the DAP.

CFs decreased as the phantom weight or height increased, which agrees with the findings of Servomaa and Tapiovaara (24). They evaluated the effects of patient weight and height on the CF in the abdominal anteroposterior projection for 5-year-old patients by using the Monte Carlo technique with the same program and mathematic phantom as in our study.

If the weight increases, the mathematic phantom is magnified in the x- and y-axes. Then the ratio of the body volume in the exposure field to the total body volume becomes smaller, and the effective dose divided by the DAP decreases as a result. In addition, subcutaneous fat increases as the mathematic phantom is magnified in the x- and y-axes, and the organs are shielded by the fat. These are the reasons why the CF decreased as phantom weight increased. In the direct measurement for our study, only the shielding by increased subcutaneous fat was simulated, since magnification of the human-shaped phantom did not occur.

In the case of increased height, the mathematic phantom is magnified in the z-axis. The magnification in the z-axis also changes the ratio of the body volume in the exposure field to the total body volume and affects the CF. For the organs outside the exposure field, the distance from the exposure field to the organ increases, and the scattered radiation decreases.

The tube voltage will affect the CF, too. Hart et al (25) evaluated the effects of tube voltage on the CF for abdominal posteroanterior projections in adult patients by using the Monte Carlo technique. In their study, CFs increased as the tube voltage increased. In our study, the tube voltage increased as the phantom size increased, while the CF decreased. Phantom size probably affects the CF more than does the tube voltage.

Our study had some limitations. First, we used a single angiography unit. Recently, several other angiography units have become available for 3D imaging, and the differences in the geometric physical relationships of the units and the angiographic parameters, especially additional filtration and tube voltage, affect the CF.

Second, we used only a 40-cm FOV (24-cm FOV at the axis of rotation), since

only this size of FOV is practical for abdominal examinations in adult patients. However, smaller FOVs can be used for children, and the difference in the FOV may affect the CF.

Third, both the direct measurements and calculations are for relatively small patients. The DAPs and effective doses for patients with weight above the range in our study will be higher. Moreover, the additional filtration and tube voltage will be changed for these larger patients, and that will affect the CF. The CFs should be evaluated with different angiography units, additional filtration, tube voltages, and FOVs for other body parts.

Fourth, the DAPs in our study were not actual values measured with a DAP meter but instead were values calculated by the angiography unit, and the uncertainty of the calculated DAPs may have affected the results. According to the data provided by the manufacturer, the uncertainty of the calculated DAPs is within 30%. However, the Monte Carlo program we used calculated the organ doses and effective dose as values per unit DAP, and the calculated CFs (effective doses per unit DAP) were independent of the actual DAP values. The CFs calculated with the Monte Carlo technique corresponded well with those obtained by direct measurement.

In conclusion, the DAPs are useful for estimating the effective dose during 3D abdominal angiographic imaging.

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