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The effective dose assessment of C-arm CT in hepatic arterial embolisation therapy

^{1,2,3}Y-S TYAN, MD, PhD, ²Y-Y LI, BS, ²M-C KU, MD, ²H-H HUANG, MD and ^{2,3}T-R CHEN, PhD

¹School of Medicine, Chung Shan Medical University, Taichung, Taiwan

²Department of Medical Imaging, Chung Shan Medical University Hospital, Taichung, Taiwan

³School of Medical Imaging and Radiological Sciences, Chung Shan Medical University, Taichung, Taiwan

Address correspondence to: Dr Tou-Rong Chen

E-mail: trchen@csmu.edu.tw

Objective: To assess the effective dose of the liver C-arm computed tomography (CT) scan during hepatic arterial embolisation surgery with clinical dose-area product (DAP) data from Taiwan.

Methods: The experiment used two kinds of phantoms: RANDO[®] Man and RANDO Woman (The Phantom Laboratory, Salem, NY), embedded with thermoluminescent dosimeters at locations according to the International Commission on Radiological Protection 103 report. The conversion factors of DAP to effective doses for males and females, respectively, were obtained. The clinical DAP data of liver C-arm CT scan during hepatic arterial embolisation surgery were collected in a hospital in Taiwan.

Results: There were 125 liver transarterial embolisation therapy cases, including 94 males and 31 females, from February 2009

to June 2010. C-arm CT was used 38 times for males and 17 times for females. The corresponding average and standard deviation of clinical DAP were $61.0 \pm 6.6 \text{ Gy cm}^2$ and $52.2 \pm 8.3 \text{ Gy cm}^2$, respectively.

Conclusion: The DAP of RANDO Man and RANDO Woman phantoms simply scanned by C-arm CT are much lower than that of patients. After consideration of the clinical DAP of patients, the effective doses of a liver C-arm CT scan recommended for males and females in Taiwan are $11.5 \pm 2.3 \text{ mSv}$ and $11.3 \pm 3.0 \text{ mSv}$, respectively.

Advances in knowledge: The conversion factors of DAP to effective doses for males and females are $0.19 \pm 0.03 \text{ mSv Gy}^{-1} \text{ cm}^{-2}$ and $0.22 \pm 0.05 \text{ mSv Gy}^{-1} \text{ cm}^{-2}$. Only if the actual DAP value of a patient scan is multiplied by the conversion factor can the correct effective dose be determined.

According to global cancer statistics, liver cancer is the fifth most common form of cancer in males, but the mortality rate is the second highest; in females, liver cancer is ranked seventh, and the mortality rate is the sixth highest. Asia has the highest incidence of liver cancer in the world, with averages of 35.5 males and 12.7 females diagnosed with liver cancer per 100 000 people [1]. Transarterial embolisation (TAE), an invasive treatment, involves the insertion of a catheter from the groin artery and the release of a contrast agent from time to time to reveal the location of the intra-vascular catheter. To achieve treatment, after the catheter is guided to a specific artery location, chemotherapy drugs are injected through the catheter to poison the tumour and embolise the vascular supply of nutrition to the tumour. However, the catheter is guided from the groin artery to hepatoma vascular structures using a perspective view from fluoroscopic images, and this approach is not always successful. When the blood path is tortuous, the fluoroscope must be projected from different angles to distinguish overlapping tissues or organs, and then to determine the correct positions of the blood vessels. However, since the vessel path is sometimes extremely complex, three-dimensional (3D) images from CT or the axial plane (axial view) will increase surgical success and shorten the fluoroscopy time. With recent advancements in computers and image plates, the cone beam X-ray tube and the image plate mounted on the ends of a C-arm fluoroscope cone beam X-ray detector can also produce CT images [2,3]. These images are hereinafter referred to as C-arm CT images. This C-arm CT can provide real-time 3D or axial cross-sectional images. Such images can help physicians to judge the directions of the blood vessels and increase the chances that hepatic chemo-embolisation surgery will be successful [4]. Although the application of C-arm CT may shorten the surgical time and radiation dose of fluoroscopy, C-arm CT angiography still requires the radiation dose. The effective dose of a C-arm CT body scan is about 6.6–9.2 mSv [5–7]. Such an effective dose is considerable, similar to the dose of multidetector computed tomography (MDCT), and it is relatively larger than the dose in general diagnosis photography. To be consistent with the “as low as reasonably possible” (ALARA) principle, physicians should be cautious in applying C-arm CT.

This study investigates the effective dose for male and female anthropomorphic phantoms scanned by C-arm

CT in liver embolisation surgery. The dose–area product (DAP) conversion to effective dose factors was estimated for male and female phantoms, respectively. The DAP data of clinical TAE surgery scanned by a liver C-arm CT protocol were collected in a hospital in Taiwan. We obtained the effective doses of clinical liver C-arm CT scans of patients via the conversion factors of male and female phantoms.

METHODS AND MATERIALS

Angiography system

The angiography system is a Siemens Axiom Artis dBA (Siemens Healthcare, Forchheim, Germany) equipped with a 40×30 cm CsI flat detector. A cone beam 3D CT reconstruction is produced from the acquisition of two-dimensional projection images by rotating the C-arm with the X-ray tube and image receptor around the patient. The CT-like images from the Siemens angiography system are named DynaCT. DynaCT has two modes of auto-exposure control (AEC) protocols: 8 s and 20 s of scan time. The abdomen C-arm CT scan adopts the 8-s mode for clinical patients in the hospital. The 8-s mode, with a scan range from right anterior oblique (RAO)100° to left anterior oblique (LAO)111°, includes 211° and a total of 419 exposure images. The 3D and CT-like axial images were reconstructed from these 419 images.

RANDO® phantom

In our study, we used two RANDO phantoms: RANDO Man (RAN 110) and RANDO Woman (RAN 100) produced by the Phantom Laboratory (Salem, NY). RANDO Man, 175 cm tall and weighing 73.5 kg, was used to simulate a male adult [8]. RANDO Woman, 163 cm tall and weighing 54 kg, was used to simulate a female adult. Both phantoms, which have no arms or legs, are constructed with a natural human skeleton cast inside a soft-tissue-simulating material. The lungs are moulded to fit the contours of the natural rib cage. The air spaces of the head, neck and stem bronchi are duplicated. Each phantom is sliced at 2.5-cm intervals into a total of 35 sliced sections. Holed grid patterns can be drilled into the sliced sections for the insertion of thermoluminescent dosimeters (TLDs).

Thermoluminescent dosimeter

TLDs, LiF:Cu,Mg,P (GR-200A, circular chips 4.5 mm in diameter and 0.8-mm thick; Solid Dosimetric Detector and Method Laboratory, Beijing, China), were

Table 1. The tissues, thermoluminescent dosimeter (TLD) locations, number of TLDs, slice location of TLDs and male and female tissue weighting factors according to the International Commission on Radiological Protection 103 report

Tissues	Locations	Number of TLDs	Slice location	Male	Female
Lung	Lung	18	13–18	0.120	0.120
Stomach	Stomach	12	20–22	0.120	0.120
Colon	Colon	12	24–32	0.120	0.120
Breast	Breast	4	17	0.120	0.120
Gonads	Gonads	4	34/30 ^a	0.080	0.080
Thyroid	Thyroid	4	9–10	0.040	0.040
Oesophagus	Oesophagus	6	8–16	0.040	0.040
Liver	Liver	12	19–23	0.040	0.040
Bladder	Bladder	4	31–33	0.040	0.040
Brain	Brain	5	2–5	0.010	0.010
Salivary glands	Salivary glands	4	6–8	0.010	0.010
Bone surface ^b	Bone surface	NA	NA	0.010	0.010
Skin	Skin	8	6–32	0.010	0.010
Bone marrow (red) ^c	Cranium	3	1–2	0.015	0.015
	Mandible	2	7	0.001	0.001
	Scapulae	3	12	0.006	0.006
	Clavicles	2	11	0.002	0.002
	Sternum	3	12–13	0.003	0.003
	Rib	6	13–19	0.010	0.010
	Os Coxae	4	28–29	0.004	0.004
	Femoral head and neck	2	33	0.017	0.017
	Vertebrae (cervical)	2	8–9	0.013	0.013
	Vertebrae (thoracic)	5	12–19	0.017	0.017
	Vertebrae (lumbar)	5	23–27	0.027	0.027
	Sacrum	4	29–30	0.005	0.005
Remainder	Heart	6	17–18	0.012	0.012
	Thymus	6	12–13	0.012	0.012
	Extrathoracic region	5	5–9	0.012	0.012
	Gallbladder	2	23	0.012	0.012
	Pancreas	3	22–23	0.012	0.012
	Spleen	5	21–23	0.012	0.012
	Adrenals	2	22–23	0.012	0.012
	Kidneys	6	23–26	0.012	0.012
	Small intestine	5	24–27	0.012	0.012
	Uterus/cervix	4	31	NA	0.012
	Prostate	2	34	0.012	NA
Sum		180	1–34	1.000	1.000

NA, not applicable.

^aMale gonads located in the 34th slice and female gonads located in the 30th slice of the phantom.

^bThe tissue weighting factor of the bone surface is 0.01. We adopted the average dose of 12 types of bones for the absorbed dose calculation of bone marrow (red) in our study as the absorbed dose of the bone surface.

^cThe weighting factors for each kind of bone are according to mass distribution and percentage of bone marrow (red) in the bone [16]. The total tissue-weighting factor of bone marrow (red) is 0.12. The RANDO® phantom, having no arms, has no humerus position available for insertion of TLDs. Therefore, the proportion of 1.9% for the humerus is based on the proportions allocated to the other 12 kinds of bones.

used to evaluate the dose in the environment and in the RANDO phantoms [9,10]. The GR-200 series TLD, which has an extremely low detection threshold ($\sim\mu\text{Gy}$ level) and an effective atomic number (Z) of 8.2, is nearly equivalent to air ($Z=7.8$) or tissue ($Z=7.4$) [11,12]. Its unique features make it an ideal environmental, personal and medical dosimeter [13,14]. All TLDs were pre-annealed at 240°C for 10 min using a Barnstead/Thermolyne 47900 Furnace (Barnstead/Thermolyne Corp., Dubuque, IA). The TLD irradiations were repeated three times using a ^{137}Cs source (beam code: INER-1002, Institute of Nuclear Energy Research, Taiwan) with an air kerma rate of 6.12 mGy h^{-1} to obtain the mean responses and their uncertainties. TLDs with uncertainties of response of $<5\%$ were selected for the experiment. After sorting, the TLD chips were then calibrated by an 85 kVp X-ray (Philips X-ray tube, type: RO 1750, tube housing assembly inherent filtration 2.5 mmAl; Philips Medical Systems, Hamburg, Germany) to correct the energy dependence of TLDs. The irradiation process was repeated three times, and a mean response (nC) was obtained for each chip. Each chip had its own sensitivity correction factor; *i.e.* electric charge (nC) transfers to the absorbed dose (mGy). A total of 180 TLDs were used to directly measure the radiation doses of the RANDO phantom being X-ray scanned. The dose response of each TLD was read out from a Harshaw model 3500 reader (Thermo Fisher Scientific, Marietta, OH). The X-ray dose was identified by a solid detector (BarraCUDA MDP, RTI Electronics, Inc., Mölndal, Sweden) calibrated by the Institute of Nuclear Energy Research in Taiwan.

TLD distribution method

The numbers and locations of TLDs in the RANDO phantom were decided mainly according to the tissue-weighting factor of the International Commission on Radiological Protection (ICRP) 103 report and the size of the organ [15]. The tissues, locations, number of TLDs and tissue-weighting factors for the male and the female are shown in Table 1 [15,16].

Clinical scan data collection

The clinical data of C-arm CT liver scans in TAE surgery were collected from a medical centre located at central Taiwan. In total, there were 125 cases of liver TAE surgery, including 94 males and 31 females, from February 2009 to June 2010. C-arm CT scans were used 38 times among 94 males, for an average of 0.40 times per person, and 17 times among 31 females, for an average of 0.55 times per person. The number of clinical investigations, frequency, tube voltage and DAP of the C-arm CT scan are shown in Table 2. The age, height, weight and body mass index (BMI) of the patient population for males and females are also shown in Table 2. The conversion factors obtained from the experiment of TLDs and RANDO phantoms were used to calculate effective doses of the 55 clinical DAP data.

RESULTS

The scan projection radiography is imaged before routine performance of the C-arm CT scan. The computer system of the C-arm instrument calculates the tube current and the tube voltage of the C-arm CT applications according to the information from the scan

Table 2. The number of TAE patients, frequency, age, height, weight, BMI, tube voltage and DAP of patient population who undergo the C-arm CT scan

February 2009 to June 2010	Male ^a	Female ^a	Total or mean ^a
Persons (TAE)	94	31	125
Frequency (DynaCT)	38	17	55
Age (y)	59 ± 8 (42–73)	54 ± 13 (20–68)	57 ± 11 (20–73)
Height (cm)	165 ± 6 (156–177)	157 ± 4 (150–164)	163 ± 7 (150–177)
Weight (kg)	64 ± 9 (52–94)	57 ± 10 (46–69)	63 ± 10 (46–94)
BMI (kg m^{-2})	23.4 ± 3.4 (18.3–32.6)	23.0 ± 3.3 (19.1–27.9)	23.3 ± 3.3 (18.3–32.6)
kVp	95.8 ± 4.0 (92–104)	93.6 ± 3.2 (90–100)	95.1 ± 3.9 (90–104)
DAP (Gy cm^2)	61.0 ± 6.6 (47.0–75.5)	52.2 ± 8.3 (41.6–66.9)	58.3 ± 8.2 (41.6–75.5)

BMI, body mass index; DAP, dose-area product; TAE, transarterial embolisation therapy.

^aData are given as number or mean $\pm$ standard deviation (range).

projection image. Generally, the tube voltage remains the same, but the tube current varies greatly in the AEC mode of the Siemens C-arm CT scan. For example, the tube current for an obese person is much greater than that for a slim person. The abdomens of RANDO Man and RANDO Woman are quite different, with thicknesses of 23.0 and 18.5 cm, respectively, in the liver layer. The BMIs, 24.0 kg m^{-2} and 20.3 kg m^{-2} , respectively, of RANDO Man and RANDO Woman are also quite different. The differences in thickness and BMI resulted in a difference in the applied tube current of almost 1.7 times, as determined by AEC mode. Therefore, the DAP of the C-arm CT scan for RANDO Man is much greater than that of RANDO Woman. Table 3 shows the height, weight, BMI of RANDO Man and RANDO Woman and the parameters and DAP of liver C-arm CT scans for both phantoms. The effective dose and standard deviation of RANDO Man and RANDO Woman as assessed by 180 TLDs scanned by C-arm CT are shown in Table 4.

DISCUSSION AND ANALYSIS

The assessed effective doses of RANDO phantoms scanned by C-arm CT are often taken to directly represent the effective doses for humans. However, Tables 2 and 3 show that the DAP of a RANDO phantom scanned by C-arm CT does not reflect, or even approach, the DAP of a human. The DAP values of RANDO Man and RANDO Woman, 43.5 Gy cm^2 and 25.7 Gy cm^2 , respectively, are even less than the minimum clinical DAP data for males and females. The clinical minimum DAP value corresponds to a male patient with a BMI of 20.7 kg m^{-2} (47.0 Gy cm^2), which is less than the BMI of RANDO Man (24.0 kg m^{-2}).

Table 3. The simulated height, weight, body mass index (BMI), scan parameter and dose-area product (DAP) of liver C-arm CT for two kinds of RANDO® phantom

Parameters	RANDO® Man	RANDO Woman
Height (cm)	175	163
Weight (kg)	73.5	54.0
BMI (kg m^{-2})	24.0	20.3
kV	90	90
mAs	370 mA $\times$ 4.3 ms	223 mA $\times$ 4.3 ms
DAP (Gy cm^2)	43.5	25.7

Table 4. The organ doses and International Commission on Radiological Protection (ICRP) 103 effective dose and standard deviation of two kinds of phantoms on liver C-arm CT scan

Tissues	RANDO Man (mSv)		RANDO Woman (mSv)	
	Mean	SD	Mean	SD
Lung	0.58	0.35	0.38	0.17
Stomach	2.20	0.83	1.57	0.69
Colon	1.40	0.89	1.40	0.77
Breast	0.83	0.08	0.19	0.05
Gonads	0.02	0.00	0.04	0.01
Thyroid	0.03	0.01	0.01	0.00
Oesophagus	0.37	0.32	0.11	0.13
Liver	0.86	0.12	0.61	0.13
Bladder	0.02	0.00	0.02	0.00
Brain	0.00	0.00	0.00	0.00
Salivary glands	0.00	0.00	0.00	0.00
Bone surface	0.03	0.03	0.02	0.01
Skin	0.04	0.03	0.04	0.03
Bone marrow (red)	0.44	0.32	0.23	0.18
Remainder	1.36	0.20	1.00	0.38
Total	8.17	1.35	5.59	1.15

SD, standard deviation.

Similarly, the minimum DAP value (41.6 Gy cm^2) corresponds to a female patient with a BMI of 19.1 kg m^{-2} , which is also less than that of RANDO Woman (20.3 kg m^{-2}). Although clinical data show that a greater BMI increases the value of the DAP in the C-arm CT scan, in comparison with the BMIs of phantoms, we cannot find its relevance to the clinical DAP data. From Tables 2 and 3, it is clear that the BMIs of phantoms fall within the BMI range of mean ± 1 standard deviation of the patient population. Hence, the reason why the DAP values of phantoms are far less than the clinical DAP of patients may not only be owing to the differences in BMI between RANDO phantoms and patients but also to certain design features of the phantoms. One is the presence or absence of arms. In actual clinical scans of patients, the patients' arms are included, but the phantoms used to simulate the patient had no arms. The lack of arms of the RANDO phantom is offset by the C-arm CT having the AEC function to

Table 5. The effective doses, dose-area product (DAP) and DAP-effective dose conversion factors (f) of RANDO® Man and RANDO Woman scanned by liver C-arm CT

Phantom	RANDO Man	RANDO Woman
Effective dose (mSv)	8.17 ± 1.35	5.59 ± 1.15
DAP (Gy cm^2)	43.5	25.6
f ($\text{mSv Gy}^{-1} \text{cm}^{-2}$)	0.188 ± 0.032	0.218 ± 0.045

reduce the exposure current, thereby resulting in a lower DAP. The reason why the DAP of RANDO phantoms is smaller than the clinical DAP could be the relatively small BMI of RANDO Woman, while it could also be lack of arms. Another possibility is the materials and structural design of the RANDO phantoms. These possibilities are worthy of further study.

The DAP values of RANDO Man and RANDO Woman are seriously underestimated, as they are only 71% and 49% of the clinical DAP values of Taiwanese males and females, respectively. Therefore, the effective dose obtained simply from RANDO phantom data cannot represent the effective doses for real persons in clinical scans. For correct and complete assessment, the effective dose must include the clinical DAP data in this study. Table 5 shows the DAP effective dose conversion factors (f) of RANDO Man and RANDO Woman as

calculated by the DAP values in Table 3 and the effective doses in Table 4.

The conversion factors of RANDO Man and RANDO Woman are $0.19 \pm 0.03 \text{ mSv Gy}^{-1} \text{cm}^{-2}$ and $0.22 \pm 0.05 \text{ mSv Gy}^{-1} \text{cm}^{-2}$, respectively. Table 6 compares our data with that of others [17–19]. Unlike the data from others, which are based on a single gender of phantom, two kinds of phantom, male and female, were used to evaluate the effective doses. Of course, in our study, the more clearly defined scan region is the liver organ. The conversion factors in the study were assessed from both phantoms without arms. The fact that the phantoms have no arms is a limitation of our study. This lack of arms could greatly affect the assessment of the conversion factor and the effective dose.

The exposure angle and rotation range of the Siemens Artis dBA C-arm CT (RAO100–LAO111°, range 211°) are similar to those of other C-arm CT. The angle and rotation range of the Philips Allura Xper DF20/10 (Philips Medical Systems, Best, Netherlands) are RAO103.5–LAO103.5° and a range of 207°. The angle and rotation range of the GE Innova 4100 (GE Healthcare, Waukesha, WI) are RAO103–LAO91° and a range of 194°. The detector plane dimensions of the Philips, GE and Siemens are 38×30, 40×40 and 40×30 cm, respectively. The distances from source to image plane are 120, 118 and 120 cm, respectively [17]. Although the scan modes of different manufacturers do differ slightly, most of the exposure angles and rotations

Table 6. Comparison of the conversion factors, C-arm CT, scanned region and methods

C-arm CT ^a	Scanned region	f ($\text{mSv Gy}^{-1} \text{cm}^{-2}$)	Author	Methods
Siemens Artis dBA	Liver (male)	0.19 ± 0.03	This study	Experiment ^b
Siemens Artis dBA	Liver (female)	0.22 ± 0.05	This study	Experiment ^c
Siemens Artis dTA	Abdomen	$0.18/0.15^d$	Suzuki et al [17]	Experiment ^e /Monte Carlo
GE Innova 4100	Abdomen	$0.29/0.32^d$	Suzuki et al [17,18]	Experiment ^e /Monte Carlo
Philips Allura Xper D20/10	Abdomen	$0.38/0.45^d$	Suzuki et al [17]	Experiment ^e /Monte Carlo
Philips XperCT	Lung	0.27	Hwang et al [19]	Experiment ^f

TLD, thermoluminescent dosimeter.

^aSiemens Artis dBA is manufactured by Siemens Healthcare, Forchheim, Germany; GE Innova 4100 by GE Healthcare, Waukesha, WI; and Philips Allura Xper D20/10 and Philips Xper CT by Philips Medical Systems, Best, Netherlands.

^bTLDs+RANDO® Man phantom.

^cTLDs+RANDO Woman phantom.

^dThe conversion factors correspond to the methods of the experiment and Monte Carlo, respectively.

^eRadiophotoluminescent glass dosimeter equipped with the RANDO-woman phantom.

^fRANDO Woman phantom+radiophotoluminescent glass dosimeters.

Table 7. The clinical dose-area product (DAP) and effective doses of liver C-arm CT scan for males and females calculated by the conversion factors

Clinical data and ED	Male	Female	Average ^a
DAP (Gy cm ²)	61.0±6.6	52.2±8.3	58.3±8.2
ED (mSv) ^b	11.5±2.3	11.3±3.0	11.4±2.5

^aWeighted by the frequency of the gender.

^bED (effective dose)=DAP×f.

are in fact similar. Thus, the conversion factors in the study could be applied to other C-arm CT liver scans.

The clinical effective doses of the liver C-arm CT scan, calculated by the conversion factor of RANDO with TLDs and the clinical DAP data are presented in Table 7.

Experimental results show that the effective doses of C-arm CT scans focused on the liver region are 11.5±2.3 mSv and 11.3±3.0 mSv for male and female patients, respectively, using a Siemens Axion dBA device in a hospital in central Taiwan. On average, a liver C-arm CT scan entails an exposure of 11.4±2.5 mSv. The clinical effective doses for male and female patients are

1.3 times and 2.2 times greater than the effective doses for RANDO Man and RANDO Woman, respectively. This assessment of clinical effective doses is mainly based on the clinical DAP data collected from liver C-arm CT scans. The assessed effective dose in the study (11.4±2.5 mSv) is higher than those in other studies (6.6–9.2 mSv) [5–7]. The effective doses of Bai et al's and Liu et al's studies were derived only from experiments with a male phantom with TLDs embedded, without using clinical DAP data for correction [5,6]. The effective doses of Wielandts et al's study were from the Monte Carlo simulation of PCXMC using a lower DAP value (45.3 Gy cm²) than that in our study (58.3±8.2 Gy cm²) [7]. The effective doses directly measured with RANDO phantoms are underestimated, particularly those measured with a RANDO Woman.

CONCLUSION

The conversion factors of the liver C-arm CT scan are 0.19±0.03 mSv Gy⁻¹ cm⁻² and 0.22±0.05 mSv Gy⁻¹ cm⁻² for males and females, respectively. The DAP are 61.0±6.6 Gy cm² and 52.2±8.3 Gy cm² for males and females, respectively. The effective doses of C-arm CT during liver TAE surgery in Taiwan are 11.5±2.3 mSv for males and 11.3±3.0 mSv for females.

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