EXTRA RADIATION DOSE OF LUNGS IN MALE EXAMINEES DURING CARDIAC COMPUTED TOMOGRAPHY

by

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Scientific paper
http://doi.org/10.2298/NTRP1704350T

The use of multi-detector row computed tomography in cardiac examinations is increasing globally. Several hospitals are yet to establish a practical method for evaluating the extra scattering dose in the lungs (D_{lung}) of male examinees with different body-weights undergoing cardiac computed tomography. To measure the dose in each slice of a lung ($D_{lung,i}$), thermoluminescent dosimeters are inserted into Rando and tissue-equivalent phantoms made of polymethylmethacrylate and derived from ICRU 48 with masses from 10 to 90 kg. D_{lung} was evaluated by weighing the scanned volume of each slice. A practical method for determining D_{lung} involves 64-slice computed tomography scans using a Philips Brilliance computed tomography at 120 kV and 200 mAs, with a thickness of 1.0 mm. $D_{lung,i}$ increased with distance from the scanning region. This experiment yielded D_{lung} values from 12.1 2.1 mSv (90 kg) to 23.0 3.8 mSv (10 kg). Finally, a simple equation can be used to derive the relationship between D_{lung} and the body-weights of a male examinee. Experimental results are compared with others in the literature.

Key words: cardiac computed tomography, lung dose, thermoluminescent dosimeter, tissue-equivalent phantom

INTRODUCTION

Cardiac computed tomography (CT) is the most commonly used technique for diagnostic purposes. The frequency and variety of CT examinations are increasing globally [1]. According to Statistics on General Health Welfare for 2014 [2], the ten leading causes of death from 2007 to 2012 included malignant tumors and heart disease. Lung cancer is the third most deadly cancer in Taiwan, responsible for 12.21 % of cancers. In recent years, multi-detector row CT (MDCT) has been used for most cardiac CT [3], and has been increasingly used in medical diagnostic radiological examinations [3]. In a cardiac CT examination, the lung is one of the most scattering critical organs because it is in the path of the primary beam [1]. Extra scanning radiation and radiation-induced malformation are relatively high. According to the ICRP 103, the weighting factor for the lung is 0.12 indicating that the lung is a sensitive organ [4]. MDCT has recently become regarded as the imaging procedure of choice in the detection of coronary artery stenosis. Physicians and radiologists must understand D_{lung} to identify clinical indications and compare them with other examinations and protocols. CT examinees commonly ask physicians and radiologists to tell them the extra scanning doses to the lung (D_{lung}) during cardiac CT. This investigation evaluates D_{lung} and develops a practical method during cardiac CT.

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MATERIALS AND METHODS

Conducting cardiac computed tomography examinations

All CT scans were carried out using a CT scanner (Philips Brilliance 64-slice), providing quantita-

Table 1. Scanning parameters of six phantoms*

Phantom [kg]	Length [mm]	Time [s]
Rando	125	26
10	80	17.7
30	115	24.2
50	135	28.1
70	150	30.7
90	165	33.4

*1.0 mm thickness, 120 kV, 200 mAs

tive information about coronary calcium and cardiovascular risk and replacing traditional intervention examinations. Fujii *et al.*, [5] used a 16-slice CT to measure the D_{lung} for adults and pediatric patients for MDCT. A professional radiologist (Sung-Yi Tsai) with ten years of experience conducted the lung positioning of phantoms and performed cardiac scanning from slice 14 to slice 18 of the Rando phantom, and slice 13 to slice 17 of polymethylmethacrylate (PMMA) phantoms [6, 7]. Each phantom was placed on the patient table. MDCT was developed from Spiral CT. Table 1 presents the scanning parameters of six phantoms. To control errors, the routine CT examinations of a 50 kg patient, were at 120 kV at maximum tube voltage peak, 200 mAs and thickness of 1.0 mm and fixed in all experiments.

Rando and tissue-equivalent phantoms

The Rando phantom (Alderson Radiation Therapy Phantom, Radiology Support Devices, Long Beach, Cal., USA) is suitable for dosage measurements in MDCT, as it has a height of 175 cm and a mass of 73.5 kg, and is made of natural skeletal tissue and plastic tissue-equivalent materials. It comprises 36 slices, each with a thickness of 2.5 cm [1, 3, 6, 8, 9]. Figure 1 presents the outer appearance of these phantoms. Anthropometrically shaped skeletons, constructed from epoxy-resin, were used to simulate human lungs [3, 7, 8, 10]. The PMMA phantoms were based on a general human design. Each comprised 31 slices, representing the head, neck, torso and abdomen, but without arms or legs [3, 6, 10]. Each phantom

Figure 1. Use of five tissue-equivalent and Rando phantoms as patient surrogates

Table 2. Dimension and physical properties of Rando, tissue-equivalent phantoms

Phantom	Rando	Tissue-equivalent				
Weight [kg]*	70	10	30	50	70	90
Height [cm]*	94.5	50	78	84	93	112
Weight [kg]**	34.5	6.75	19.0	31.5	44.1	57
cm slice^{-1}	2.5	1.6	2.3	2.7	3.0	3.6

*original design referred from ICRU 48; **without arms and legs

was based on the GSF-Forshungszentrum für Umwelt und Gesundheit, Germany, adult mathematical models, and the lung masses were based on the ICRP reference man [6, 10]. The densities of the materials were as follows, that of the lung tissue-equivalent was 0.296 gcm^{-3}, the skeleton-cortical-bone tissue-equivalent was 1.486 gcm^{-3}, the tissue-equivalent was 1.105 gcm^{-3} [3, 6, 10]. The thermoluminescent dosimeters (TLD) were inserted into each slice through a grid of holes with diameters of 11 mm [11]. All slices of the phantoms were equally thick. Table 2 presents the dimensions and physical properties of the phantoms [6, 10].

In vivo measurements during CT examination

The effective doses can be calculated from the computed tomography dose index (CTDI) and the dose length product (DLP) displayed on the console monitor of the CT scanner. Since the lung is a large organ, during a cardiac CT examination, the lung is exposed to radiation. D_{lung} is uniformly distributed. Measurements of extra radiation are more complex than those of smaller organs. TLD-100 (Mg, Cu, and P) with dimensions of 3.2 mm 3.2 mm 0.9 mm were used herein. Three TLD were packed into one bag. Each bag was implanted at positions where Dlung was representative of the phantoms [3, 8, 12, 13]. Table 3 shows that measurements were made at 80 points on each slice of the lung and subdivided equally of the 70 kg PMMA phantom. The mean dose of that was received by each slice of the lung tissue equivalent was taken as $D_{\text{lung, i}}$.

Lung of Rando and PMMA phantoms are ranging range from slice 12 to 17 and slice 10 to 15, respectively. Each lung had six slices. Figure 2 presents the TLD that were inserted into slice 15 of a 50 kg PMMA phantom.

Most *in vivo* measurements of TLD were mainly located in the lung. Some TLD were exposed to X-rays during the CT examinations, while others were exposed to extra scattered radiation. Three individually calibrated TLD, packed into one bag, yielded three

Table 3. The 80 measured points of the PMMA phantom

Slice	10	11	12	13	14	15
Left lung	6	6	7	7	9	7
Right lung	4	6	7	8	8	5

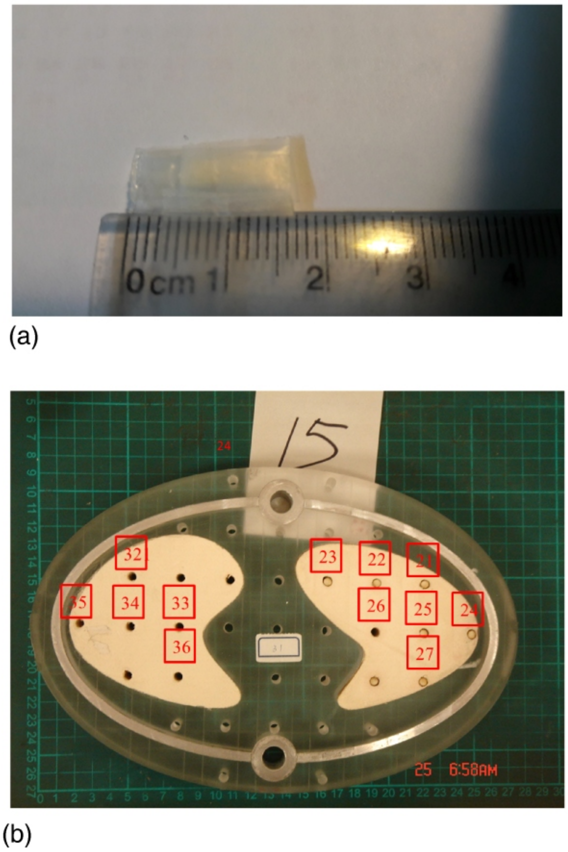


Figure 2. Three TLD were packed into one bag (a); TLD were inserted into slice 15 of a 50 kg PMMA phantom (b) (number means the TLD bag's number)

readings at each measurement location as shown in fig. 2(a). These were averaged to obtain the TLD-measured doses from which $D_{\text{lung, i}}$ was obtained. Nine TLD chips were used to measure background radiation at our low-background lab [1, 3]. Figure 3 reveals a 70 kg PMMA phantom lung slice 10 to 15. Cardiac CT scans were performed from slice 13 to slice 17. The red rectangle outlines the areas scanned by cardiac CT. Figure 4 presents a sectional view of the lung of a 70 kg PMMA phantom, comprising six slices.

Calculation of the surface area of the lung

In cardiac CT, radiation is not uniformly distributed throughout the lung. The lung can be divided into the left and the right lungs, and both can be divided into six slices yielding a total of 12 slices. The calculation of D_{lung} requires the volume of the lung associated with each slice to be determined. Based on the weighting factors in eq. 1, a slice with a larger volume has a larger weighting factor of D_{lung}. Since each slice has the same thickness, the volumes of the lung can be determined simply by calculating the cross-sectional area of each slice (tab. 3). Each slice has a different $D_{\text{lung, i}}$. eq. 1 yields D_{lung} as weighted by volume as the sum of the $D_{\text{lung, i}}$ values of all scan slices. Table 4 presents the weighting factors (%) of all parts of slices of the lung of a 70 kg PMMA phantom [13]. The following equation yields D_{lung}, taking into account the ratio of the area of the lung

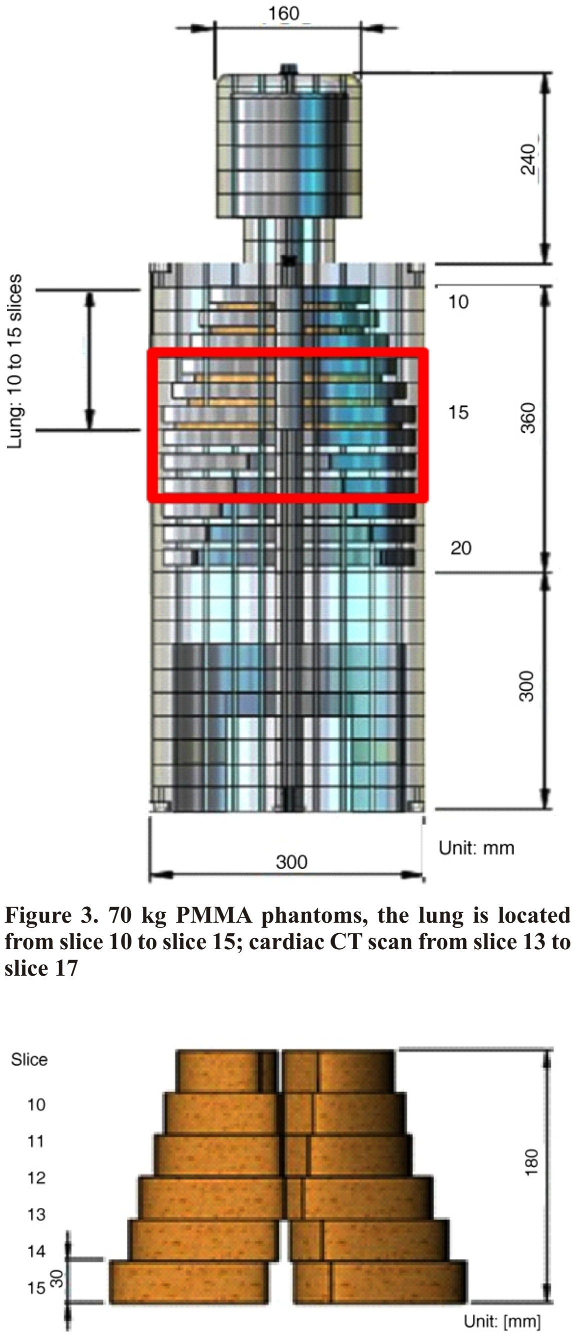


Figure 3. 70 kg PMMA phantoms, the lung is located from slice 10 to slice 15; cardiac CT scan from slice 13 to slice 17

Figure 4. Sectional view of the lung of a 70 kg PMMA phantom, comprising six slices

Table 4. The weighted factor [%] of all parts slices of left and right lungs of a 70 kg phantom

	10	11	12	13	14	15
Left lung [%]	2.27	5.80	7.71	8.43	9.18	11.7
Right lung [%]	4.96	7.01	8.61	10.2	10.5	13.7

$$D_{\text{lung}} \quad \frac{V_i D_{\text{lung,i}}}{V_i} \ (i = 10\text{-}15) \qquad (1)$$

where $D_{\text{lung, i}}$ represents the extra radiation dose to which the phantom lung at each slice is exposed. V_{i} is the weighting factor volume i (%) part of the lung slices.

Calibration of TLD-100 using ^{60}Co

To calibrate the photon dose and the linearity of TLD, TLD was irradiated using a ^{60}Co standard source with activities of 128 GBq at the Calibration Laboratory of the National Tsing-Hua University. TLD measurements were made five times with the TLDs at random locations. Taam *et al.*, stated that the energy dependence of TLD is not considered significant and is lower than 20 % [14]. The TLD-100 was selected owing to its small dimensions and the response lower dependence on photon energy, dose rate, and the direction of incidence of radiation. To ensure batch homogeneity, the TLD were irradiated as described by eq. 2.

$$ECC_i \quad \frac{Q_i \quad \bar{Q}}{\bar{Q}} 100\% \qquad (2)$$

The element correction coefficient (ECC) determined the relative sensitivity of these TLD to correct the variation among the sensitivities of the batches. ECC_i is the accuracy of the ith TLD. Q_i is the reading of the i-th TLD, and $\bar{Q}$ is the average of all TLD readings in the calibration. TLD were selected with a 10 % accuracy [3, 6, 7, 11]. The selected TLD chips were annealed and read using a fully automated Harshaw 3500 reader (Bicron NE, Solon, O., USA). The read-out was a two-step procedure: first, in a microprocessor-controlled oven, the TLD were heated using a Barnstead/Thermolyne 47900 Furnace (Thermolyne Co.) to 50 °C, which temperature was held for 1s; second, they were heated at a rate of 10 $°Cs^{-1}$ to 240 °C, which temperature was held for 1s, they were then cooled rapidly on an aluminum block [3, 6, 7, 15]. These TLD have been established to be accurate dosimeters for use in CT examinations. To optimize the annealing procedure, the TLD were always handled with great care to prevent direct contact with dirt or hands [3, 6, 11].

RESULTS

TLD calibration and uncertainty

The response of the TLD-100 to 100 Sv, 500 Sv, 1 mSv, 2 mSv, 2.5 mSv, 5 mSv, and 7.5 mSv photons in the range studies was linear. The conversion factor for the TLD-100 was Y [mSv] = $-8.16\ 10^{-2}$ + + $1.14\ 10^{-1}$[nC] (TLD), and the square of the correlation coefficient (R^2) was 0.9992 [3]. The precision and accuracy of the TLD-100 were determined by many factors, including the following. Mainly from (1) systematic uncertainties in the readings made using the Harshaw 3500 reader ranged from 10 to 12 %; (2) TLD calibrations of the ^{60}Co source, the homogeneity, and the exposure to low X-rays were within 10 %; (3) TLD counting statistical errors, ranging from 8 % to 10 % were effectively suppressed; (4) the uncertainty of the PMMA phantom set to 5 %, includes scan ranges of the cardiac CT in each phantom and non-tissue-equivalent effects because the phantoms were constructed entirely as described in the ICRU report 48 [6, 10]; (5) to calibrate the area of each lung slice, uncertainty ranged from 3 % to 5 %; (6) errors in power fluctuations from the Philips CT scanner were obtained from monthly clinical quality assurance (QA) tests and found to be less than 2 %. Table 5 listed the total uncertainties which ranged from 17.4 % to 19.9 %. Tseng estimated uncertainty to be less than 20 % [6, 11].

Table 5. The total uncertainties presented in this study

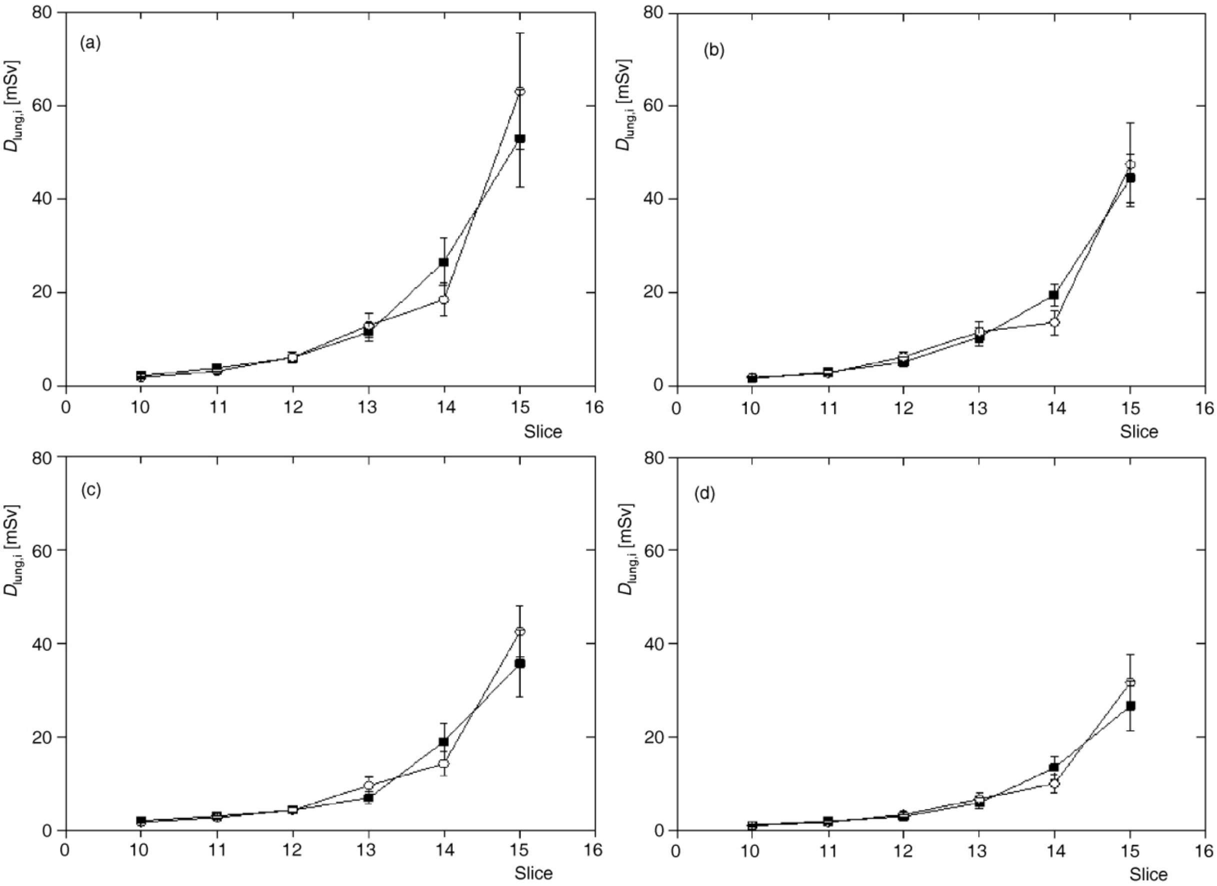
Source	One standard deviation (Δ_i)
Variation of the Harshaw 3500 reader	10 %-12 %
Calibration of the ^{60}Co source	10 %
TLD counting statistics	8 %-10 %
Non-tissue equivalence effects of the PMMA phantom	5 %
Area of the lung slice	3 %-5 %
CT scanner fluctuation	<2 %
Δ_{tot}	17.4 %-19.9 %

D_{lung} distribution among the left and right lungs in the phantom

The increase in $D_{lung,\ i}$ from the 10th slice to the 15th slice reveals that D_{lung} increases by five for PMMA phantoms. The $D_{lung,}$ 10 of the left lung 10th slice is 3.15 % more than D_{lung}, 15 of the 15th slice. The dose of the right lung 10th slice is 4.08 % of the 15th slice, revealing that $D_{lung,\ i}$ decreased greatly with the scanning region in the cardiac CT examination. The D_{lung} values of the left and right lungs of the 10 kg phantom were larger than those of all other phantoms. Figure 5 shows $D_{lung,\ i}$ [mSv] ranging from 10 to 15 slice of right and left of the phantoms.

D_{lung} values of male examinees with various body-weights

Figure 6 reveals that the estimated D_{lung} decreased as body-weights increased. The highest D_{lung} was measured in the 10 kg phantom. TLD were inserted into the Rando lung, and the Philips 64 CT was set to 120 kV and 200 mAs. D_{lung} from slice 12 to slice 17 was 12.4 1.9 mSv, measured at 26 locations. Three TLD were placed into one bag. D_{lung} for the Rando phantom was approximately 1.06 times that of the 70 kg PMMA, which was 11.6 2.0 mSv. The primary differences may arise from (1) inconsistent lung densities (2) the lung volume between Rando and PMMA phantoms. The error bars represent uncertainty in the D_{lung} values. The regression equation D_{lung} [mSv] = -0.14 W [kg] + 23.3 has an R^2 which is 0.89257, indicating that TLD is a good method for evaluating the D_{lung} of PMMA phantoms.



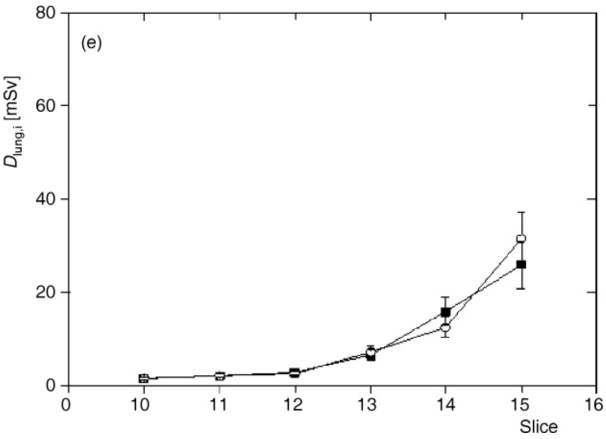


Figure 5. $D_{lung,\,i}$ **[mSv] ranging from 10 to 15 slice of right (■) and left (□) of (a) 10 kg, (b) 30 kg, (c) 50 kg, (d) 70 kg, and (e) 90 kg PMMA phantoms**

DISCUSSION

Comparison of D_{lung} with other studies

Many papers on cardiac CT doses and methods of measuring them have been published. Practical methods for determining the extra radiation doses absorbed by large organs, D_{lung} of these PMMA phantoms. To compare D_{lung} results with other studies, the phantoms used and the exposure factors must be considered. In this investigation, Rando and PMMA phantoms were used. The data in tab. 6 revealed that it was similar to the D_{lung} that was delivered at the coronary artery calcium scoring with MDCT.

Alonso *et al*. [1] studied the breast and nearby organs for unshielded and shield exposures with bismuth during lung CT examinations. The D_{lung} values of the right and left parts of the lung were 11.5 0.5 and 12.5 0.3 mSv during thoracic CT scans without bismuth shielding, respectively. Geleijns *et al*. utilized the Philips Tomoscan LX CT with 120 kV and 333 mAs, for chest examination with a Pb thickness of 10 mm. The researchers inserted TLD-100 into the Rando phantom without considering the relationship between D_{lung} and the body-weights of the examinee, yielding a D_{lung} of approximately 44 mSv [16, 17].

Chan *et al*. stated a D_{lung} value of 3.86 2.35 obtained by a coronary angiograph and 31.4 20.2 mSv

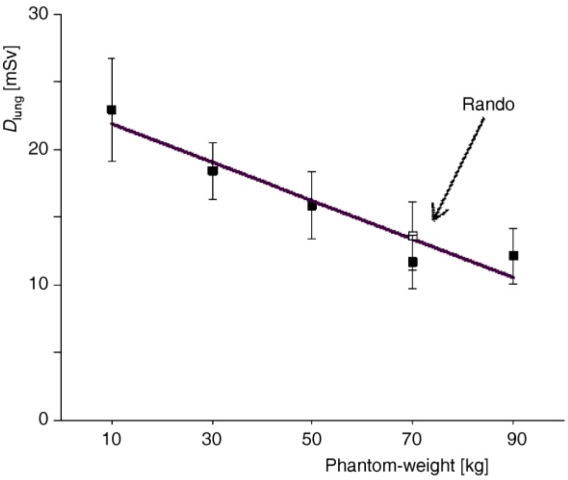


Figure 6. Estimate of D_{lung} as a function of different body-weights of a male examinee

by calcium scoring CT using TLD [8]. Gonzaga *et al*. found that the 16-slice cardiac CT provided doses of greater than 17.5 mSv with an error of 12 % of the Brilliance 6 during chest CT. Gonzaga also found that D_{lung} depended on many protocol-related parameters [12].

Feng *et al*. measured the D_{lung} from the thorax CT in a 64-slice MDCT using an anthropomorphic phantom that represented a five-year-old child, and found a D_{lung} of 5.41 mSv [18].

Mori *et al*. inserted many TLD into the whole body, exposing it to intense radiation during 16 and 64 cardiac multislice CT (MSCT). Radiation exposures of a Rando phantom in 256, 64, and 16 MSCT were evaluated at 45   20, 85.0   30.1, and 77.1   36.7 mSv, respectively. D_{lung} is higher than the corresponding values for any other organs [9].

Einstein *et al*. determined the radiation exposure for a standardized male phantom (computational model) using 64-slice Computed Tomography Coronary Angiography (CTCA), and found D_{lung} values from 42 to 91 mSv [19]. Fujii *et al*. utilized 32 photodiode dosimeters that were embedded within anthropomorphic phantoms of six-year-old children (20 kg, 115 cm) and adults (61 kg, 170 cm). In routine adult chest CT, D_{lung} values ranged from 11.1 to 25.8 mSv and in routine pediatric chest CT, D_{lung} values ranged from 2.2 to 10.6 mSv [5, 16].

A D_{lung} of is 37.44 mSv was obtained in CT examinations of the chest using a Toshiba Aquilion MDCT with settings of 120 kV and 350 mAs, and a scan area of 300 mm [15]. Hunold *et al*. measured the cardiac CT dose using a Siemens 4 CT, inserting TLD into a Rando lung under measurement conditions of 120 kV, 300 mA, and 400 mAs. D_{lung} was 37.6 mSv at the 17th slice using eight TLD. Hunold *et al*. found that MDCT always yielded a higher effective dose than the

Table 6. Extra lung equivalent dose undergoing cardiac CT examinations

CT	Dose [mSv]	Treatment	Reference
This study	12.4 1.9 (Rando)	Cardiac CT	
16 MSCT	11.5 0.5 (right)	Thoracic CT	1
Bright speed 16 MSCT	12.5 0.3 (left)		
Philips Tomoscan LX CT	44		17
Brilliance 16	17.5 12 % (Rando)	Chest CT	12
Brilliance 6	11.1 12 % (Rando)	Chest CT	12
Bright speed 4	11.3 13 % (Rando)	Chest CT	12
Somatom sensation 64-MDCT	3.86 2.35	Calcium scoring	8
Somatom sensation 64-MDCT	31.4 20.2	Coronary angiography	8
64-slice MDCT	5.41	5 years, 19 kg	18
256 MSCT	45 20		9
64 MSCT	85.0 30.1		9
16 MSCT	77.1 36.7		9
Toshiba aquilion 16-slice	23.4	Adult chest CT (61 kg, 170 cm)	5
Toshiba aquilion 16-slice	24.9	Adult chest CT (61 kg, 170 cm)	5
Toshiba aquilion 16-slice	6.2	Pediatric chest CT (20 kg, 115 cm)	5
Siemens somatom 16-slice	11.1-25.8	Adult chest CT (61 kg, 170 cm)	5
Siemens somatom 16-slice	19.3	Pediatric chest CT (20 kg, 115 cm)	5
Siemens somatom 16-slice	2.2-10.6	Pediatric chest CT (20 kg, 115 cm)	5
Somatom 64-slice	42 mSv for **ECTCM	***CTCA	17
Somatom 64-slice	58 mSv for ECTCM	120 kV	17
Toshiba, aquilion	37.44	Chest CT	15
Siemens 4-slice	37.6	MDCT	15
*EBCT	2.6	Calcium scoring	20
EBCT	3.9	Coronary angiography	20

* EBCT: Electron beam CT; **ECTCM: Electrocardiographically controlled tube current; ***CTCA: Computed tomography coronary angiography

electron beam CT (EBCT). They used a tube voltage of 140 kV, yielding a D_{lung} of 2.6 mSv by calcium scoring and 3.9 mSv by coronary angiography [20]. In addition, no equation for estimating Dlung is in terms of body-weights. There are is no exactly D_{lung} for each slice in the Hunold *et al*. study [20].

The variations in the results of the aforementioned investigations have two causes. The first is variations among exposure factors, such as tube voltage, number of scans, tube current, and CT-modality. The second is the measurement locations on the lung. In addition, patients were worried about the organ most radiosentive to radiation, the gonad, which ranged from 1.50 to 2.20 mSv because of its long distances from cardiac.

This investigation has some limitations. First, the PMMA phantom cannot simulate cardiac motion. PMMA phantoms represent discrete weight-specific examinee groups. The shapes and size of examinees obviously vary, even among examinees of equal age. Second, automatic tube current modulation can effectively reduce the radiation dose inside the CT scanning region.

CONCLUSION

The information investigation is useful for determining the D_{lung}, which serves as a reference for clinical radiology doctors and radiologists. The optimizing protocol is important for improving technique and reducing unnecessary exposure to of the lung. In cardiac CT examinations, the lung was the organ that received the highest radiation when scanned. As the weight of PMMA phantoms increased, D_{lung} decreased. The linear equation D_{lung} [mSv] = –0.14 W [kg] + 23.3 yielded an R^2 of 0.89257, indicating that the TLD method is effective for evaluating extra radiation to which lungs in PMMA phantoms are exposed. It is very important to evaluate extra radiation doses during the cardiac CT examination of different body-weight examinees as future investigations.

AUTHORS' CONTRIBUTIONS

The idea and results for the presented research were initiated and performed by C.-Y. Chen. The data processing and graphic presentation, manuscript preparation, were carried out S.-Y. Tsai, H.-C. Tseng, Z. Ruan, Z. Xu, Y. Liao, and S.-P. Changlai. Theoretical analysis was carried out by S.-Y. Tsai and all the authors participated in the discussionn of the results presented in the final version of the paper.

ACKNOWLEDGEMENT

The authors would like to thank the staffs of Putian University Hospital for their efficient supports. Financial assistances was partly provided by the Ministry of Science and Technology of the Republic of China under Contract no. MOST 105-2314-B-040-010.

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Received on July 22, 2017
Accepted on Septembar 22, 2017

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АПСОРБОВАНА ДОЗА ОД РАСЕЈАНОГ ЗРАЧЕЊА У ПЛУЋИМА МУШКИХ ПАЦИЈЕНАТА ПОДВРГНУТИХ КАРДИОЛОШКОМ ПРЕГЛЕДУ КОМПЈУТЕРИЗОВАНОМ ТОМОГРАФИЈОМ

Примена компјутеризоване томографије са мултидетекторским редовима при кардиолошким прегледима у глобалном је порасту. Болнице тек треба да успоставе практичну методу за процену дозе у плућима од расејаног зрачења мушких пацијената различите телесне масе, подвргнутих кардиолошким прегледима компјутеризованом томографијом. Како би се измерила доза у сваком слоју плућа, термолуминисцентни дозиметри постављени су унутар Рандо фантома и ткивно-еквивалентног фантома, израђених од полиметилметакрилата према ICRU 48, са масама од 10 до 90 kg. Доза је процењена на основу тежинског факторисања скениране запремине сваког слоја. За практичну процену дозе употребљени су 64-слојни томографски скенови на Philips Brilliance апарату, са параметрима експозиције 120 kV, 200 mAs и дебљином слоја од 1 mm. Доза у слоју расте са удаљавањем од области скенирања. Резултати експеримента за дозу у слоју су од 12.1 2.1 mSv (90 kg) до 23.0 3.8 mSv (10 kg). На крају, једноставна једначина се може користити како би се описала зависност дозе у слоју и телесне масе мушких пацијената. Такође, извршено је и поређење експерименталних резултата са раније објављеним подацима.

Кључне речи: кардиолошки преглед, компјутеризована томографија, доза за плућа, термолуминисцентни дозиметар, ткивноеквивалентни фантом