Investigation of spatial dose distributions for microscopic computed tomography

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Abstract: Understanding the spatial dose distributions using microscopic computed tomography (micro-CT) system is essential in investigating radiation doses received by small animals and by the working staff. The purpose of the present study is to investigate the spatial dose distributions of the Skyscan 1176 micro-CT system using thermoluminescent dosimeter TLD-100H. In this study, 180 TLD-100H chips and a Harshaw TLD readout system were used. TLD-100H chips were placed outside the scanning chamber and various positions of the instrument surface. The results showed that as the distance increase, the measured doses at the central axis of the scanning rotation decreased. The doses measured on the instrument surface are low (02.4-11.9μSv), and are close to the minimal detectable dose (1 μSv) of the TLD-100H. The mean measured dose at the control console was 5.4 μSv ± 2.84 μSv/month. In conclusion, the TLD-100H dosimeters are good candidates for dose monitoring in micro-CT study. Most of the scattered radiation of the Skyscan 1176 micro-CT can be attenuated by the shielding door and the doses received by the operator at the control console are acceptable.

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1. Introduction

In the field of diagnostic radiology, X-ray computed tomography (CT) is widely considered an important imaging modality because the CT image can provide the detailed in vivo anatomy structure of the study subject. During the early years, commercially available CT was not useful for laboratory investigations of small animals owing to limitations in spatial resolution. Over the past decades, however, improvements of spatial resolution and scanning speed have made it practical to obtain such high-resolution CT images of small animals during research investigations. Recently, microscopic CT (micro-CT) system has been used in the biomedical imaging field to obtain the anatomic images of small animals (1,2).

Improving the quality of micro-CT images is an issue with growing importance in the biomedical imaging field. Several studies have provided useful approaches to achieve this purpose (1,2). To our knowledge, however, studies on radiation dosimetry for micro-CT are rare and are mostly focused on estimating the dose received by small animals for a specific imaging procedure (3). Recently, some studies have indicated that the radiation doses from the micro-CT system are high enough where changes in the immune response and other biological pathways may alter the experimental outcomes (1,3). Although the radiation doses used for micro-CT are generally not lethal to small animals, reducing the delivered dose may be useful in developing a new imaging technique and in studying an optimized setting of imaging parameters.

Understanding the spatial dose distributions using micro-CT system is essential in investigating radiation doses received by small animals and by the working staff. In a previous study, thermoluminescent dosimeter TLD-100H demonstrated the advantage for low-dose measurements in diagnostic radiology (4). The purpose of the present study is to investigate the spatial dose distributions of the micro-CT system using thermoluminescent dosimeter TLD-100H.

2. Material and Methods

Instrument

The Skyscan 1176 (Skyscan, Antwerp, Belgium) micro-CT system was used in this study (Figure 1). The Skyscan 1176 uses air-cooled sealed-type X-ray source, which allows a spatial resolution of 14 μm under tube potentials ranging from 20 kV to 90 kV (5). The basic radiation shielding around the scanning chamber ranges from 1 mm to 3 mm Al, supported with 2 or 3 mm Pb, depending on the angles around the gantry coronal plane. During the scanning procedure, the shielding door is typically closed, and the carbon fiber bed is moved to the scanning chamber. In the current study, the most frequently used imaging parameters for animal scanning were employed, namely, tube potential of 90 kV, tube current of 260 µA (the total exposure time automatically changed according to the number of projections), and Cu filter thickness of 0.11 mm. The X-ray tube and detector rotated 1° for every single exposure (360°/projection). No animal or animal phantom was used during the imaging procedure.

Figure 1 The Skyscan 1176 micro-CT system.

Calibration of TLD and signal response analysis

Here, 180 TLD-100H chips (Bicron) and a Harshaw TLD readout system (Model 5500) were used. During the preparation stage, a group-annealing-and-sorting procedure was applied to minimize potential variations between the TLD-100H chips (6). All TLD-100H chips were annealed in groups for 10 min at 240 °C, and then cooled down to room temperature. The reading cycle settings of the system were as follows: 35 s for reading time, 4 °C s−1 heating rate, a reading temperature range of 100 °C to 240 °C and, a pre-annealing temperature of 100 °C (7).

In the calibration procedure, all the TLD-100H chips and a calibrat

Dose measurements for the micro-CT system

Dose measurements at the central axis of the scanning rotation

Three TLD-100H chips were placed at the center of a carbon fiber bed and scanned with tube potential of 90 kV. This was done to measure the doses at the central axis of the scanning rotation. Various numbers of scan projections (1, 3, 5, 7, and 10) were used to investigate the dosimetry characteristics of the micro-CT system.

Dose measurements on the instrument surface and the control console

In order to explore the dose distributions due to scattered radiations and to explain the doses received by the working staff, it is essential to estimate the spatial dose distributions outside the scanning chamber. To measure spatial dose distributions outside the scanning chamber, a 50 × 60 × 22 cm3 wooden frame was built and placed inside the shielding door (Figure 2). Each TLD-100H chip was packed and attached at various positions of the wooden frame. The translation stage was removed from the micro-CT system before setting up the wooden frame.

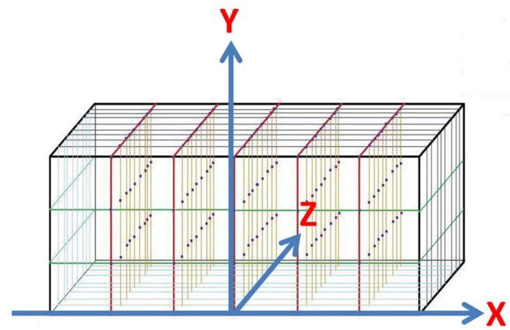
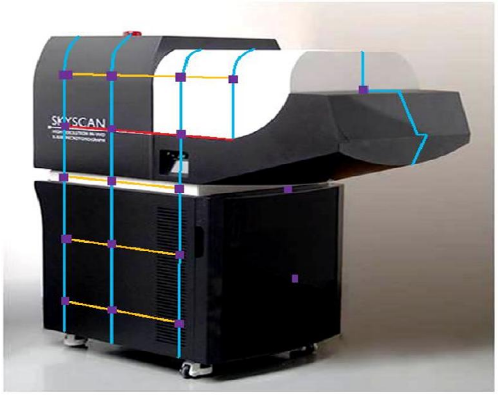


Figure 2 The positions of TLDs inside the shielding door.

The TLD-100H chip was packed and attached to various positions of the instrument surface in order to measure the transmitted and scattered radiations of the micro-CT system (Figure 3). A total of 45 TLD-100H chips were used.

Next, the doses on the control console were measured to simulate the dose received by the working staff. Three TLD-100H chips were placed on the control console, which was 60 cm away from the micro-CT system. Once all the TLD-100H chips were deployed, the wooden frame and all TLD-100H chips were scanned with tube potential of 90 kV. Various numbers of scan projections (1, 3, 5, 7, and 10) were applied. Then, the background radiation was measured in a physician's office, which was 10 m away from the micro-CT scanning room. After scanning, all the TLD-100H chips were readout using the procedure mentioned earlier.



(a)

(b)

Figure 3 (a) The positions of TLD on the right side of instrument surface. (b) The positions of TLD on the left side of instrument surface and control console.

3. Results and discussion

Signal response analysis for TLDs

Figure 4 shows the signal responses for TLDs as a function of delivered doses. Each point in the figure corresponded to an average of three readings, and a linear fit was applied to the data points. The determination of coefficient (R2) to the tube potential of 90 kVp was 0.999 for doses ranging from 0 mSv to 12510 mSv. The fitted function was then used in the dose calculation for further TLD measurements.

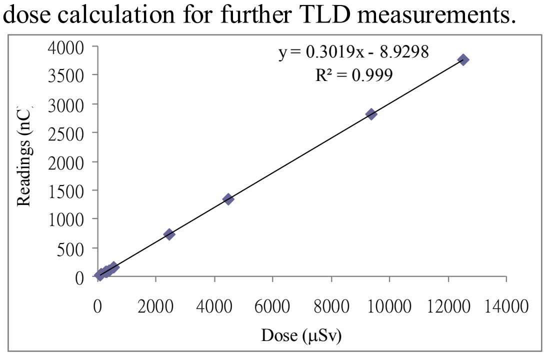


Figure 4 The signal responses for TLDs.

ose measurements at the central axis of the scanning rotation

Dose measurement at the central axis of the scanning rotation inside the scanning chamber can reflect the combination of the primary radiation and scattered radiation. Figure 5 shows the measured doses corresponding to various numbers of the projections. As can be seen, the measured dose ranged from 2,453 μSv to12,509 μSv. A linear fit was applied to these data points, and the determination of coefficient (R^2) was 0.9944.

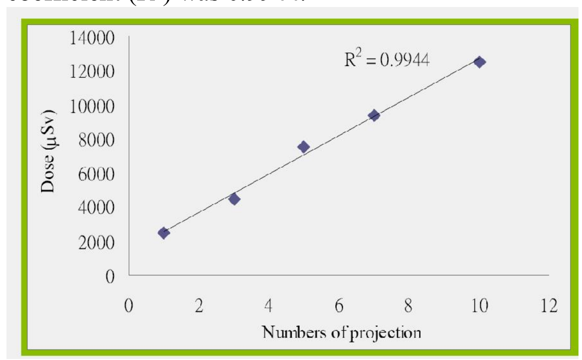


Figure 5 The measured doses corresponding to various numbers of projections

Spatial dose distributions outside the scanning chamber

In order to explore the dose distributions due to scattered radiations and to explain the doses measured on the instrument surface, it is important to estimate the spatial dose distributions outside the scanning chamber. Figure 6 showed the spatial dose distributions at the central axis of the scanning rotation (x=0) outside the scanning chamber. The x-axis in the figure represents the distance between measurement point and the boundary of the scanning chamber. The results showed that as the distance increase, the measured doses decreased. The inverse square fit was applied to these data sets, and the values of R2 ranged from 0.9855 to 0.998.

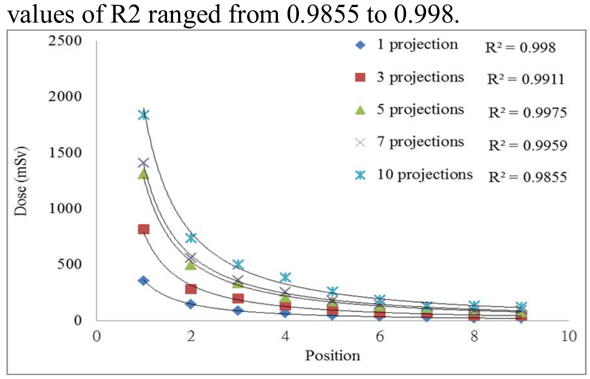


Figure 6 The spatial dose distributions at the central axis of scan rotation (x = 0) outside the scanning chamber.

Table 1 shows the spatial dose distributions on the left (x<0) and right (x>0) sides inside the shielding door. The mean doses on each side were calculated from 54 chips of TLD measurements. A linear correlation analysis was conducted to investigate the relationship between the mean doses and the projection numbers. The correlation coefficients were 0.9951 and 0.9988 for the left and right sides, respectively. The mean doses measured on the left side were higher than those measured on the right side.

Table 1 The mean dose and dose range of left and right sides inside the shielding door.

Numbers of projection	Left side		Right side	
	Mean dose (μSv)	Dose range (min-max) (μSv)	Mean dose (μSv)	Dose range (min-max) (μSv)
1	34.3	3.4-179.9	28.4	3.7-141.8
3	67.3	9.3-290.8	55.2	6.7-236.0
5	108.7	9.0-618.5	80.7	9.6-358.6
7	128.2	8.7-657.2	100.4	9.4-434.2
10	173.4	7.1-986.1	135.7	8.3-650.5

Figure 7 shows the measured doses inside the shielding door at the planes, which are closest to the instrument surface. The results showed that the variation of doses was significantly dependent on the measurement position of TLD. In general, the measured dose on the left side was higher than the measured dose at the corresponding point on the right side.

			37.4	71.4	126.0	7.1	77.4			
			55.8	80.6	80.0	72.2	73.0			
			61.8	42.7	80.5	84.5	71.8			
37.4	55.8	61.8	61.8	42.7	80.5	84.5	71.8	71.8	73.0	77.4
70.6	88.0	72.6	72.6	72.2	94.6	90.6	81.8	81.8	99.0	80.4
73.7	118.5	84.8	84.8	67.0	122.2	134.8	121.6	121.6	123.2	86.5
58.2	126.4	130.5	130.5	136.0	125.2	147.9	110.2	110.2	145.8	105.5
96.3	141.9	113.8	113.8	85.0	173.6	200.7	126.2	126.2	175.4	154.3
120.9	188.4	129.4	129.4	183.6	223.8	210.5	148.8	148.8	174.1	171.7
166.2	179.4	50.6	50.6	190.5	295.2	299.4	66.5	66.5	193.5	219.0
125.2	20.4	10.4	10.4	147.2	337.0	175.0	13.3	13.3	37.8	118.7
13.7	14.4	8.3	8.3	10.5	28.6	12.0	7.1	7.1	11.6	18.6
			8.3	10.5	28.6	12.0	7.1			
			14.4	89.0	1091.0	121.4	11.6			
			13.7	650.5	1842.0	986.1	18.6			

Figure 7 The measured doses inside the door at the planes which closest to the instrument surface.

Doses on the instrument surface and the control console

Table 2 shows the spatial dose distributions on the left (x>0) and right (x<0) sides of the instrument surface. The mean doses on each side were calculated from 17 chips of TLD measurements. A linear correlation analysis was conducted to investigate the relationship between the mean doses on the instrument surface and the projection numbers. The correlation coefficients were -0.1847 and -0.1283 for the left and right sides, respectively. The maximum difference in mean doses measured on the left and right side was 0.8 (4.9 to 4.1) μSv. In addition, the mean measured dose at the control console was 6.4 μSv ± 2.1 μSv.

Table 2 The spatial dose distributions of left and right sides on the instrument surface.

Numbers of projection	Left side		Right side	
	Mean dose (μSv)	Dose range (min-max) (μSv)	Mean dose (μSv)	Dose range (min-max) (μSv)
1	5.6	2.4-10.8	5.4	2.7-8.1
3	7.7	4.3-11.9	7.0	5.1-11.1
5	4.9	2.4-9.6	4.1	1.4-8.3
7	7.5	4.1-11.7	7.4	4.7-10.4
10	5.1	2.9-10.7	4.8	3.0-7.8

Signal response analysis for TLDs

Dose measurement for a low radiation dose exposure is a technical challenge. Results from our previous study show that applying calibration factors to the TLD dosimeters is crucial, especially in low-dose measurements, because greater variations in sensitivity are likely to occur in individual TLD dosimeters under such conditions. The TLD-100H dosimeters have advantages, such as a high sensitivity and linear responses at low doses, which makes them suitable for dose monitoring of micro-CT in the current study.

Doses at the central axis of the scanning rotation

Results from the dose measurement at the central axis of the scanning rotation inside the scanning chamber show that the output of X-ray of the Skyscan 1176 micro-CT is very stable, for example, the measured doses are proportional to the numbers of projections. As the total numbers of projection of an animal study vary depending on the animal size and requirement of the study, the results obtained in the present work may be suitable for estimation of total radiation doses delivered to the animal.

In addition, the doses measured inside the scanning chamber are significantly higher than the scattered radiation doses measured along with the central axis of scan rotation outside the scanning chamber. This effect can be attributed to the dose measured inside the scanning chamber, including the primary radiation and scattered radiation; however, the dose measured outside the scanning chamber includes only the scattered radiation.

Spatial dose distributions outside the scanning chamber

In the present study, the scattered radiation doses measured along with the central axis of the scanning rotation is proportional to the inverse square of the distance between the point of measurement and the boundary of the scanning chamber. This is due to the fact that the intensity of scatter radiation is decreased with the distant and the scattered radiations seem to be emitted in a cone shape through the boundary of the scanning chamber.

Furthermore, the authors also observed that the spatial doses measured outside the scanning chamber are linearly proportional to the numbers of projections, and that the doses measured on the left side are higher than those measured on the right side. Such asymmetrical spatial dose distribution may be caused by the slight thickness difference of the shielding material used in the construction of the scanning chamber (1 mm to 3 mm Al supported with 2 or 3 mm Pb). The thinner thickness of the shielding material may have resulted in higher radiation dose.

Doses on the instrument surface and the control console

The doses measured on the instrument surface and the control console are low, and are close to the minimal detectable dose (1 μSv) of the TLD-100H. The doses are also significantly lower than the maximal annual dose limit (50 mSv) of the radiation working staff. An interested finding from this study is that the doses measured on the instrument surface show no significance, in relation to the numbers of projection contrary to the dose measured outside the scanning chamber. In addition, the difference in the mean doses measured on the left and right side may not be significant, because this difference in dose is less than the minimal detectable dose of the TLD-100H. These effects are caused by the sufficient thickness of the shielding door of the Skyscan 1176 micro-CT. Therefore, no additional shielding is needed.

Limitations

The results obtained in the present study may only be suitable for the Skyscan 1176 micro-CT. Several other limitations should also be considered. First, only a tube potential of 90 kVp is used in this study, which is also the most widely used X-ray potential for animal studies. To the authors' knowledge, the tube potential of lower kVp may result in lower penetration of scattered radiation that, in turn, leads to lower spatial doses. Second, doses from the sample were not used and the bed did not move during the scanning procedure. Therefore, the radiation attenuated by animals cannot be accurately estimated in the present study.

4.Conclusions

By applying suitable calibration procedure, the TLD-100H dosimeters are good candidates for dose monitoring in micro-CT study. Results from the present study show that most of the scattered radiation of the Skyscan 1176 micro-CT can be attenuated by the shielding door. The doses received by the operator at the control console are also acceptable. In addition, the results may be helpful for the estimation of radiation doses delivered to animals in a micro-CT scan.

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