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Practical alignment method for X-ray spectral measurement in micro-CT system based on 3D printing technology

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Abstract

This study presents a practical alignment method for X-ray spectral measurement in a rotating gantry based micro-computed tomography (micro-CT) system using three-dimensional (3D) printing technology. In order to facilitate the spectrometer placement inside the gantry, supporting structures including a cover and a stand were dedicatedly designed and printed using a 3D printer. According to the relative position between the spectrometer and the stand, the upright projection of the spectrometer collimator onto the stand was determined and then marked by a tungsten pinhole. Thus, a visible alignment indicator of the X-ray central beam and the spectrometer collimator represented by the pinhole was established in the micro-CT live mode. Then, a rough alignment could be achieved through repeatedly adjusting and imaging the stand until the pinhole was located at the center of the acquired projection image. With the spectrometer being positioned back onto the stand, the precise alignment was completed by slightly translating the spectrometer-stand assembly around the rough location, until finding a “sweet spot” with the highest photon rate and proper distribution of the X-ray photons in the resultant spectrum. The spectra were acquired under precise alignment and misalignment of approximately 0.2, 0.5, and 1.0mm away from the precise alignment position, and then were compared in qualitative and quantitative analyses. Qualitative analysis results show that, with slight misalignment, the photon rate is reduced from 1302 to 1098, 1031, and 416 photons/second (p/s), respectively, and the characteristic peaks in the acquired spectra are gradually deteriorated. Quantitative analysis indicates that the energy resolutions for characteristic peak of $K_{\alpha 1}$ were calculated as 1.56% for precise alignment, while were 1.84% and 2.40% for slight misalignment of 0.2mm and 0.5mm. The mean energies were reduced from 43.93keV under precise alignment condition to 40.97, 39.63 and 37.78keV when misaligned. Accurate spectral measurements in micro-CT systems are significantly influenced by the alignment precision. This practical alignment method using 3D printing technology could be readily applied to other rotating gantry based micro-CT systems with modified design of the supporting structures and careful considerations of the spectrometer and gantry dimensions.

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Keywords

spectral measurement; micro-computed tomography (micro-CT) system; spectrometer placement; rough and precise alignment

1 Introduction

The knowledge of X-ray spectra plays an important role in various medical imaging research, such as calculating the radiation dose delivered to the object, optimizing imaging parameters, selecting spectral filtrations, and improving dual or multi energy imaging performances [Boone *et al* 2004, Zhang *et al* 2012, Ay *et al* 2009, Karellas and Vedantham 2008]. The measurement method of X-ray spectra using compound semiconductors, such as cadmium zinc telluride (CdZnTe) and cadmium telluride (CdTe) has been well developed [Zhang *et al* 2012, Zhang *et al* 2008, Ren *et al* 2014]. In this method, precise alignment between the radiation source and the spectral detecting device (spectrometer) is vital and usually achieved with the aid of lasers, pinhole collimators and other optical components [Zhang *et al* 2008, Brezovich and Jordan, 2007, Bottigli *et al* 2008].

However, these regular alignment methods specifically proposed for general X-ray imaging systems being operated in open space can't be directly applicable or transferrable to a rotating gantry based micro-computed tomography (micro-CT) system [Ren *et al* 2016, Ghani *et al* 2016]. This type of micro-CT system doesn't provide the possibility to change the scanner geometry easily, meaning that normally the source-to-detector distance (SDD) is completely fixed and extremely limited when compared to a micro-CT prototype system [Jantanayingyong *et al* 2010]. In addition, the X-rays backscattered inside the gantry are not negligible due to the short SDD. Therefore, it is necessary to develop a specific alignment method for the X-ray spectral measurement in rotating gantry based micro-CT systems without introducing additional backscatters.

In recent years, three-dimensional (3D) printing technology has been widely used in various applications with very high efficiency and accuracy [Gross *et al* 2014]. In this study, supporting structures including a stand and a cover are manufactured using a 3D printer to facilitate the spectrometer system placement inside the gantry and to assist the alignment procedure. The spectra acquired under precise alignment and slight misalignment conditions are compared qualitatively and quantitatively.

2 Materials and Methods

2.1 Description of micro-CT scanner and spectrometer system

The micro-CT scanner (Quantum FX, Perkin Elmer, Waltham, MA, USA) utilized in this study mainly consists of a polychromatic X-ray source (target: tungsten) and a flat panel X-ray imaging detector. The source and detector are mounted on the opposite sides of a rotating gantry with a fixed SDD of 265mm. The nominal voltage and current ranges of the X-ray source are 30 to 90kVp and 20 to 200μA, respectively. Besides the CT scan mode that develops a tomographic image, a live mode lasting up to 150 seconds is available to view the

subjects in real time with/without rotating the gantry, providing the possibility of achieving spectral alignment and measurement.

The spectrometer system (XR-100T-CdTe, Amptek, Bedford, MA, USA) utilized in this study includes an X-ray and gamma ray detector (energy resolution: 570eV at 60keV corresponding an energy resolution of 0.95%), a preamplifier and a cooler system using $3 \times 3 \times 1 \text{ mm}^3$ CdTe diode detector mounted on a two-stage thermoelectric cooler [O'dwyer and Tichner 2007]. In order to acquire an acceptable photon rate level to prevent spectral pile-up distortions, the sensitive element of the detector is covered by a specific collimation set (Collimation Kit, Amptek, Bedford, MA, USA) including three small diameter tungsten pinholes with 2mm in thickness and a brass spacer (36mm in length and 3000 μm in diameter) separating them. The detailed schematic of the collimation set is illustrated along with the spectrometer placement in Fig. 1, where above the spacer are two pinholes with 200 μm and 1000 μm diameters, and one below with 400 μm diameter. The collimation configuration is vital to reduce the received photon count rate during the X-ray spectral measurement process considering the extremely limited space inside the gantry and strong exposure, even with a minimum current of 20 μA applied. This restriction of detection area, however, results in a major difficulty of achieving precise alignment for X-ray spectral measurement.

2.2 3D printed supporting structures and the advantages

As shown in Fig. 1, the gantry was fixed at the upright position with the X-ray source at the top and the flat panel detector placed at the bottom, and therefore, the spectrometer needed to be placed upright toward the X-ray source. In order to facilitate the spectral measurement, supporting structures including a stand and a cover were fabricated to support the spectrometer system while leaving sufficient space for power supplies as well as connectors and to protect the flat panel detector from excessive pressure, respectively. These two structures were specifically designed by AutoCAD software and printed by a desktop 3D printer (Makerbot replicator, Makerbot, Brooklyn, NY, USA) using filament of poly-lactic acid (PLA).

Compared to conventional machining technique using materials such as metals, plastic and wood, 3D printing has more advantages in facilitating biomedical researches as in this study. First, 3D printing could be easily mastered and is accessible for all researchers even without prior machining experiences because the operation of a 3D printing system is sufficiently simple and safe.

Second, 3D printing provides competitive positioning precisions of 0.0004 inch in XY plane (horizontal) and 0.0001 inch in Z direction (vertical). Also, the paper-thin layers (100 μm) ensure professional quality and high resolution of printed models, thus no further sanding, finishing, or postproduction is needed.

Third, the infill of the filament of PLA could be set as low as 1% (lower inset in Fig. 1) during the printing process while maintaining a very high solidity. This low percentage of infill has essential impacts: 1) it significantly lowers the cost of printing because it uses less materials; 2) due to the lower utilization of PLA, the printed models have lower weight

compared to those if machined using other regular materials in conventional machining, as calculated in Table 1, and therefore have less pressure upon the platform such as the cover and the flat panel detector in this study; 3) the lower infill of PLA makes 3D printing a fast process from several minutes to a couple of hours, depending how low the infill percentage is and how many layers are needed, in comparison to a couple of days for conventional machining including the transportation time and communication efforts; 4) most importantly, less backscattered X-rays are caused inside the printed models, compared to a full infill of those created in conventional machining, because more X-ray photons from the primary beam could penetrate through the model rather than being interacted and backscattered, and then influencing the precise spectral measurement.

2.3 Two-step approach for spectral alignment

As shown in Fig. 1, even with careful calculations to reduce the cover thickness and to lower the spectrometer position, the source-to-spectrometer distance was still quite small due to the extremely limited space inside the gantry. Based on the estimated distances from the focal spot to the top (18mm) and the bottom (60mm) of the spectrometer collimator, the diameter of the acceptance aperture projected onto the plane of the focal spot was approximately less than 1mm, indicating that the spectral alignment and the received photon rate were very sensitive to the lateral spectrometer position [Zhang *et al* 2012]. Therefore, a good alignment of the spectrometer-stand assembly to the X-ray central beam was crucial for an accurate spectral measurement. Also it should be noted that considering the extremely limited distance between the X-ray focal spot and the collimator front surface, none useful information of guiding the alignment process would be observed in the acquired projection image if the spectrometer-stand assembly was directly imaged in the micro-CT live mode. Thus, a practical approach for spectral alignment and measurement in the rotating gantry based micro-CT system was proposed with two steps, a rough alignment without putting the spectrometer system onto the stand and a precise alignment through translating the spectrometer-stand assembly.

First, according to the relative position between the spectrometer system and the stand, the upright projection of the spectrometer collimator down to the stand was determined and then marked by a tungsten pinhole (2mm thick with a 2000 μ m hole), as shown in Fig. 2. Thus, without positioning the spectrometer system on the stand, a visible alignment indicator of the X-ray central beam and the spectrometer collimator (represented by tungsten pinhole) could be established in the micro-CT live mode. In order to make sure that the spectrometer surface was perpendicular to the central beam, meaning that the tilting angle between the printed structure and the flat panel detector was acceptable (assuming that the flat panel detector is right perpendicular to the X-ray central beam), the diameters of the pinhole in two mutually perpendicular directions in the resultant projection image were calculated and compared.

Afterwards, the spectrometer was positioned back onto the stand and the precise alignment was achieved by slightly and gradually translating the spectrometer-stand assembly around the rough location back and forth until finding a “sweet spot” with the highest photon rate and proper distribution of the X-ray photons in the resultant spectrum. In order to facilitate

the translation process and improve the translation efficiency and accuracy during both rough and precise alignments, two strategies were adopted to the printed cover. One was to press the cover closely against the sides of the gantry so that it is not shifted when moving the stand. The other was to mark the cover top with two-dimensional (2D) coordinates, assisting to record the positions of the stand, so that the stand can be located in the right place determined in the rough alignment process after mounting the spectrometer. Since the stand translation was completely manual in the current study, the X-ray exposure had to completely cease during each translation.

2.4 Evaluation of measured spectra

Compared to regular spectral measurement that is operated in an open space, the measurement in a gantry based micro-CT system involves the addition of the incident primary beam and the backscattered X-rays [Benmakhlouf *et al* 2011]. Since most spectrum simulation software is developed for regular spectral measurement without considering the involvement of backscatter effect, these simulated spectra can't be directly utilized to verify the accuracy of spectral alignment and measurement in the current study. Instead, qualitative and quantitative spectral analysis was performed to emphasize the importance of precise spectral alignment and to evaluate the degradation of spectra with misalignment.

As aforementioned, qualitative analysis included the observations of the received photon rate and the presences of the characteristic peaks from the X-ray tube target. On the other hand, energy resolution of the characteristic peaks and mean energy of the whole spectrum were calculated as well for the quantitative evaluation purposes. These evaluations were important because they could indicate how the precision of the spectral measurement is influenced by the misalignment between the X-ray central beam and the spectrometer device. Energy resolution (R) of the characteristic peak $K_{\alpha I}$ was calculated using equation (1), where E_{FWHM} was the full width in energy unit at half-maximum, and E_C was the central energy (59.32 keV) of $K_{\alpha I}$ [Bushberg *et al* 2012].

$$R = \frac{\Delta E_{FWHM}}{E_C} \times 100\% \quad (1)$$

The mean energy was directly calculated from the measured spectra using equation (2), where ME was the mean energy, E was the energy for each channel, and $N(E)$ was the photon count number in the channel with energy E .

$$ME = \frac{\sum_{E=0keV}^{90keV} E \cdot N(E)}{\sum_{E=0keV}^{90keV} N(E)} \quad (2)$$

3 Results and discussion

The projection image acquired under the condition of rough alignment is shown in Fig. 3, where the two dotted lines intersect indicates the X-ray central beam direction, which coincides with the geometrical/imaging center of the flat panel detector. In order to determine the surface smoothness of the printed models and to ensure an acceptable tilting angle, the diameters of the pinhole in two mutually perpendicular directions in the projection image are calculated and compared. In Fig. 3, the diameters in the mutually perpendicular directions are 24.435mm and 24.486mm, respectively, indicating a relative difference of 0.21% and a smooth surface of the printed models and an acceptable tilting angle. Also, another important advantage of using 3D printing compared to the conventional machining is that higher imaging contrast could be achieved in the projection image due to the less infill percentage of PLA inside the printed models, as shown in Fig. 3. After achieving the rough spectral alignment, the spectrometer system was mounted on the stand and precise alignment was accomplished by slightly and gradually translating the spectrometer-stand assembly around the rough location. All the spectral measurements were performed under the identical condition of 90kVp, 20μA, collimation (Fig. 1), and duration of 100 seconds in the micro-CT live mode.

The photon rate is limited to 1338 photons/second (p/s) with precise alignment. In this condition, as shown in Fig. 4 (a) – (c), the characteristic peaks (K_{α} and K_{β}) predominating the measured spectrum (solid black curve) can be clearly distinguished. As a comparison, spectra are also measured with misalignment of approximately 0.2, 0.5, and 1.0mm away from the precise alignment position, as shown in Fig. 4 (a) – (c) as well. With misalignment, not only the photon rate is reduced to 1098p/s, 1031p/s and 416p/s, but also the whole spectral distribution is distorted. With slight misalignment of 0.2mm, a small fraction of X-ray photons in the central beam is blocked by the collimator by either absorption or scattering (with reduced photon energy). The characteristic peaks first start to deteriorate because characteristic peaks occupy discrete energies and both of the X-ray photon absorption and scattering can significantly influence and reduce the photon numbers under the characteristic peaks. On the other hand, the photon number reduction in the lower energy part in the detected spectrum seems not obvious due to the compensation of deflected photons from high energy part. With more misalignment of 0.5mm, more photons in the X-ray central beam are blocked and interacted with collimators, and the characteristic peaks are further influenced. Also, more photons with low energies can't reach the detector due to the misalignment. With further misalignment of 1.0mm which is beyond the acceptance aperture, the whole detected spectrum is totally distorted and inaccurate.

As summarized in Table. 2, the energy resolution for characteristic peak of $K_{\alpha I}$ is calculated as 1.56% under precise spectral alignment, while is 1.84% and 2.40% for misalignment of 0.2mm and 0.5mm. Since the characteristic peak of $K_{\alpha I}$ has completely diminished in the spectrum measured under misalignment of 1mm, no corresponding energy resolution can be acquired. Similarly, the mean energy is reduced from 43.93keV under precise alignment condition to 40.97, 39.63 and 37.78keV under misalignment conditions. Both energy resolution and mean energy quantitatively indicate that the accuracy of measuring spectra could be significantly influenced by the alignment precision.

Even with the coordinates marked on the cover, manual translation of the stand to reach the rough/precise alignment position is still a time-consuming process due to the cease of the X-ray exposure for each adjustment. A possible automated solution is to attach the stand and cover to a stepper motor. In this way, the translation process may be performed continuously in the micro-CT live mode, and the alignment efficiency and accuracy can be greatly improved. However, this solution would significantly increase the cost and the hardware complexity and further reduce the distance between the focal spot and the surface of the spectrometer collimator. Nevertheless, it provides the possibility to build an automated platform to realize the rough/precise alignment in rotating gantry based micro-CT systems efficiently and accurately.

4 Conclusion

In conclusion, this paper proposed a practical alignment method for spectral measurement in a rotating gantry based micro-CT system using 3D printing technology. Specifically, the alignment process was performed in two steps, rough alignment and precise alignment. The significance of precise alignment was indicated by comparing the spectral characteristics acquired under good alignment and misalignment conditions. With modified design of the supporting structures and different considerations of the system dimensions, this practical alignment method could be translated to other X-ray imaging systems with limited SDD.

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Fig. 1.
The spectrometer placement inside the gantry and the configuration of spectrometer collimator used for covering the CdTe detector.

Fig. 2.

A tungsten pinhole was used to mark the upright projection of the spectrometer collimator onto the stand; the spectrometer system was removed from the supporting system when achieving the rough alignment.

Fig. 3.

Determination of the rough alignment position through translation of the printed stand; this projection image was taken with micro-CT in live mode, the intersection of the two dotted lines indicating the X-ray central beam direction and the geometrical/imaging center of the flat panel detector.

(a)

(b)

(c)

Fig. 4. Comparisons of spectra acquired with precise alignment and misalignment of approximately (a) 0.2mm; (b) 0.5mm; (c) 1mm away from the precise alignment position, in terms of photon rate and characteristic peak features.

Weight comparison of the supporting structures printed by 3D printer and conventional machining

Table 1

Material	Density (g/cm ³)	Cover weight (g)	Stand weight (g)	Total weight (g)	Infill percentage
PLA	–	122.37	55.50	177.87	1%
Steel	7.85	1549.59	1058.06	2607.65	100%
Copper	8.94	1764.76	1204.98	2969.73	100%
Aluminum	2.71	535.35	365.54	900.89	100%
Acrylic	1.19	234.91	160.39	395.30	100%
Glass	2.50	493.50	336.96	830.46	100%
Wood	0.85	167.79	114.57	282.36	100%

Table 2

Spectrum evaluation with alignment and misalignment

Misalignment	Photon rate (p/s)	$K_{\alpha I}$ energy resolution (%)	Mean energy (keV)
0.0mm	1338	1.56	43.93
0.2mm	1098	1.84	40.97
0.5mm	1031	2.40	39.63
1.0mm	416	–	37.78