Experimental measurement of human head motion for high-resolution computed tomography system design

Liang Li
Zhiqiang Chen
Xin Jin
Tsinghua University
Department of Engineering Physics
Beijing, 100084, China
and
Ministry of Education
Key Laboratory of Particle & Radiation Imaging
Beijing, China
E-mail: liiang@tsinghua.edu.cn

Hengyong Yu
Ge Wang, FELLOW SPIE
Virginia Tech
School of Biomedical Engineering and Science
Biomedical Imaging Division
Blacksburg, Virginia 24061

Abstract. Human head motion has been experimentally measured for high-resolution computed tomography (CT) design using a Canon digital camera. Our goal is to identify the minimal movements of the human head under ideal conditions without rigid fixation. In our experiments, all the 19 healthy volunteers were lying down with strict self-control. All of them were asked to be calm without pressures. Our results showed that the mean absolute value of the measured translation excursion was about 0.35 mm, which was much less than the measurements on real patients. Furthermore, the head motions in different directions were correlated. These results are useful for the design of the new instant CT system for in vivo high-resolution imaging (about 40 μm).

Subject terms: head motion; computed tomography (CT); image reconstruction; motion artifacts.

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1 Introduction

Early diagnosis is critical for the therapies of some illnesses such as cerebrovascular disease. It requires high-resolution imaging tools in order to find small pathological characters, such as thrombus and angiomia. Although computed tomography (CT) has become a routine imaging tool for many clinical diagnoses, its image quality is still inadequate for the early diagnosis requirements. For example, 3-D CT images with a resolution of 40 μm are required for early diagnosis of cerebrovascular disease. That is about 10 times the spatial resolution of current multislice CT (MSCT), which is widely used in clinical diagnoses. In developing such a high-resolution CT system, a challenge is to suppress motion artifacts resulting from the motions of the human body during CT data acquisition.

Theoretically speaking, CT reconstructs cross-sectional images of an object from a set of projections taken from many different views. In the commercial MSCT, these projections are continually acquired over a certain period of time, with the assumption that the object being scanned is stationary. However, that assumption is impractical in clinical applications, because some motions of human organs, such as peristalsis, heartbeat, and other physiological motilities, are unavoidable. These motions may result in motion artifacts such as blurring or doubling, which are well known in medical imaging—not only CT, but also other imaging modalities like magnetic resonance imaging (MRI), position emission tomography (PET), and single-photon-emission computed tomography (SPECT).

There are several approaches to reduce the motions or motion artifacts. The first one starts from human-body research to decrease body movements, as by rigid fixation, holding breath, or drugs. Some physiological organ movements, however, are very hard to stop or decrease, such as pulse, gastrointestinal motility, and heartbeat.

Another way is to speed up the CT acquisition process to improve its temporal resolution. Such improvement is primarily limited by the gantry rotation speed in the current MSCT. The best rotation time is about 0.25 s/round. It is very hard to increase gantry rotation speed further. Rotation times of less than 0.2 s, which could provide a temporal resolution of 100 ms, are associated with more than 75 g centrifugal forces. This is beyond today’s mechanical limits. Although electron-beam scanning CT (EBCT) can accomplish a temporal resolution below 100 ms, it has never become a commercially successful CT system, due to such inherent disadvantages as a compromised signal-to-noise ratio (SNR) and limited spatial resolution.

Some other methods are also available to reduce motion artifacts, such as the dual-source CT technique, gating, and motion compensation. Also, head and body holders have been used for immobilization and repositioning to reduce movement, especially in radiotherapy. Among all these methods, the most popular one is motion compensation, which requires a motion model as a priori knowledge. Therefore, it is very helpful to measure and analyze the organ motions to improve the motion correction algorithms and optimize the scanning protocol or system design. In the past decade, the quantitative analysis of organ motion has gained increased relevance in both MRI and CT. Those studies were based on real patients. The organ motions may be quite different among the wide variety of patients.

The goal of this paper is to identify the minimal movements of the healthy human body under ideal conditions,
which may guide us in designing a new high-resolution CT system. This paper is organized as follows. Section 2 presents our devices and method for head motion measurement based on healthy volunteers. Section 3 presents the experimental results and analysis. Finally, we present our conclusion and discussion of high-resolution CT imaging.

2 Materials and Methods

Head motion measurements were carried out on 19 volunteers to simulate a typical acquisition scenario with a commercially available MSCT where the patient is lying down. The volunteers include 7 females and 12 males of ages between 22 and 49 years (mean age, 29.6 years). After informal agreement, volunteers were instructed to avoid any motion of their head as well as to stop swallowing during the scanning procedure. To fix the head in a stable position, a series of head and neck support cushions was used, as shown in Fig. 1b, which includes six cushions made of polyurethane foam with different shapes and sizes. According to their head shapes and sizes, each volunteer chose a form-fitting cushion to hold his/her head in a comfortable and relaxed position on the support table top. To provide optimum precision of measurements and ease of processing, a hair ribbon was used, as shown in Fig. 1c. A measurement point (M point) was marked on a square of white paper affixed to the ribbon. In view of the vibration of the floor and the inconsistency between the sequential pictures taken by the camera, a reference point (R point) was also marked on another square of white paper, which was affixed to an immovable trestle rigidly fixed on the support table top.

Motion was monitored using a Canon PowerShot SX1 IS digital camera [Fig. 1a] with image resolution 3840×2160. The actual frame rate of this camera was about 2.6 Hz. The camera was fixed on a tripod, which was used twice for each measurement. First, it was placed at position 1 on the x axis of the right side of the head. Then, it was placed at position 2 on the y axis of the top of the head, as shown in Fig. 2. Hence, we got two groups of pictures for each volunteer. We used a time window of 2 min for each measurement. The reason is that our ultimate goal is to make an in vivo high-resolution CT system with resolution 40 μm. That is about 10 times the spatial resolution of current MSCTs. Therefore, the areas of the detector elements and focal spot in this new system are only about 1% of the related parameters in current MSCTs. Assume that the x-ray tube in the new CT could provide the same photon output per second as the one in current MSCT. In order to ensure enough photons collected by every detector elements, the acquisition time should be extended by a factor of 10. Hence, the study was performed within 2 min for each measurement.

The measurement precision was essentially determined by the field of view (FOV) of the camera. In our arrangement, the relative accuracy for spatial resolution was about 25 μm. To verify the precision and sensitivity of the devices and method, in addition to the 19 volunteers, a plush toy mouse was measured as a stationary “volunteer” on the support table top.

The two square regions as shown in Fig. 1c were automatically segmented from the camera pictures. In these two regions, the 2-D coordinates of the M point and R point were calculated using the centroid formula,
where \( i \) denotes the pixels whose gray values are smaller than a predefined threshold, \( I \) is the number of all the pixels, \((u, v)\) are the indices of the image matrix, and \( g_i \) denotes the pixel gray value. Since the centroid calculation was related to the gray value of each pixel, the brightness of all the camera pictures should be consistent. We used a high-power lamp instead of the camera flashbulb. To reduce the influence of the vibration of the floor and the inconsistency of the sequential pictures, relative coordinates were used for each picture:

\[
\begin{align*}
t_k &= u_k^M - u_k^R, & v_k &= v_k^M - v_k^R, & k &= 1, 2, \ldots, N, \\
\end{align*}
\]

(2)

where \( T_k \) is the number of sequential pictures of volunteer \( k; N \) is the number of observation targets, which equals 20, including the 19 volunteers and the plush toy mouse; and \((u_{j,k}, v_{j,k})\) and \((u_{j,k}^R, v_{j,k}^R)\) are the coordinates of the M point and R point for picture \( t \) of volunteer \( k \), respectively.

The data for statistical analysis were recorded after the motion acquisition of each volunteer. In our study, a 3-D coordinate system was used to provide a definite description of the rigid body’s position and spatial orientation. As shown in Fig. 2, the coordinate system was defined by \( x, y, \) and \( z \) axes. The \( y \) axis was orthogonal to the longitudinal axis of the support tabletop. The \( z \) axis was parallel to the vertical axis of the human body. The orthogonal vector to the \( y-z \) plane defined the \( x \) axis. For each volunteer, more than 300 pictures were collected within about 2 min. The motions of the volunteers can be calculated from these sequential pictures:

\[
\begin{align*}
\Delta x_{t,k} &= (u_{t+1,k}^C - u_{t,k}^C) \cdot \Delta d, & \Delta y_{t,k} &= (v_{t+1,k}^C - v_{t,k}^C) \cdot \Delta d, & \Delta z_{t,k} &= (u_{t+1,k}^C - u_{t,k}^C) \cdot \Delta d, & k &= 1, 2, \ldots, N, \\
\end{align*}
\]

(3)

where \( \Delta d \) is the side of the square pixels of the pictures. In our experiments, \( \Delta d \) is about 25 \mu m, determined by the camera resolution and camera distance. Based on Eq. (2), \((u_{j,k}^C, v_{j,k}^C)\) and \((u_{j,k}^R, v_{j,k}^R)\) are the relative coordinates calculated from the pictures at the \( x \)-axis and the \( y \)-axis, respectively.

We define the mean absolute translation excursions, which were the arithmetic mean of the absolute motion ranges \( \Delta x_{t,k}, \Delta y_{t,k}, \) and \( \Delta z_{t,k} \), respectively:

\[
\begin{align*}
\Delta x_k &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} |\Delta x_{t,k}|, & \Delta y_k &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} |\Delta y_{t,k}|, & \Delta z_k &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} |\Delta z_{t,k}|, & k &= 1, 2, \ldots, N. \\
\end{align*}
\]

(4)

Translation variances were calculated for statistical registration of possible oscillating head movements,

\[
\begin{align*}
\text{variance} (\Delta x_k) &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} (|\Delta x_{t,k} - \Delta x_k|^2), & \text{variance} (\Delta y_k) &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} (|\Delta y_{t,k} - \Delta y_k|^2), & \text{variance} (\Delta z_k) &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} (|\Delta z_{t,k} - \Delta z_k|^2), & k &= 1, 2, \ldots, N. \\
\end{align*}
\]

(5)

Measurement interpretation was accomplished using exploratory data analysis with diagrams. To analyze whether the head motions on the 3-D coordinates were correlated, statistical analysis of correlation (Pearson’s coefficient) was used. The Pearson’s coefficients were defined as

\[
\begin{align*}
\rho_{x,y,k} &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} \frac{(\Delta x_{t,k} - \Delta x_k)(\Delta y_{t,k} - \Delta y_k)}{\left[ \sum_{t=1}^{T_k-1} (|\Delta x_{t,k} - \Delta x_k|^2) \sum_{t=1}^{T_k-1} (|\Delta y_{t,k} - \Delta y_k|^2) \right]^{1/2}}, \\
\rho_{y,z,k} &= \frac{1}{T_k - 1} \sum_{t=1}^{T_k-1} \frac{(\Delta y_{t,k} - \Delta y_k)(\Delta z_{t,k} - \Delta z_k)}{\left[ \sum_{t=1}^{T_k-1} (|\Delta y_{t,k} - \Delta y_k|^2) \sum_{t=1}^{T_k-1} (|\Delta z_{t,k} - \Delta z_k|^2) \right]^{1/2}}, \\
\end{align*}
\]

(6)
3 Results

All 19 volunteers had head motions during the data acquisition. Figure 3 shows the head motions traced along the $y$ axis and $z$ axis when the camera was placed on the $x$ axis of the right side of the head. The motion ranges of most of the volunteers were within ±1.5 mm. Only 3 of 19 volunteers showed a larger range (~4 to ~2 mm). In cases 5 and 16, unexpected twitches of the volunteers led to clearly perceptible motions. For healthy humans, these twitches can be avoided by good personal preparation and physical control.

Figure 4 shows the mean absolute translation excursions. In 12 of 19 cases, the mean excursions were less than 0.5 mm. In 5 cases, the mean excursions were larger than...
0.5 mm and less than 1.0 mm. There are only 2 cases whose mean excursions are larger than 1.0 mm. The mean absolute translation excursions for all volunteers (not including case 20) resulted in an average of 0.35 mm, which was only 14% of the measures on real patients by Wagner et al. Considering the spatial resolution of state-of-the-art commercial MSCTs, from our results it is easy to see why there are no or only slight artifacts observed in volume CT images. It can be summarized that the head motion may be reduced about 86% for healthy and good-self-control humans who do not suffer from the pressures of lying in the CT gantry. The translation variances are diagrammed in Fig. 5.

To describe the correlations of the motions in different directions, we calculated the Pearson’s correlation coefficients of the data along the y and z axes by Eq. (6). The results are shown in Fig. 6. According to the widely accepted standards established by Cohen, correlation coefficients $<0.3$, 0.3 to 0.5, and $>0.5$ were considered to represent small, medium, and large correlation. Of the 20 cases, 4 showed small correlation, 8 medium correlation, and 8 (including the toy mouse) large correlation. It can be concluded that the head motions in different directions are correlated.

4 Discussion and Conclusion

Our results indicate that all the healthy volunteers displayed head motions. With self-control and in the absence of pressure, the mean absolute translation excursion is about 0.35 mm, which is much less than the patients’ results in Ref. 2. Hence, we conclude the head motion of patients will not be smaller than 0.35 mm without rigid fixation. Because the best spatial resolution of the current commercial MSCTs is about 0.4 mm, the 0.35-mm motions will not result in perceptible motion artifacts, and most of them can be neglected. This is the main reason why no or only slight artifacts are observed in current volume CT images.

However, if we want to obtain higher-resolution CT images for early diagnosis of some critical diseases, these motions will lead to severe artifacts and cannot be neglected. As we mentioned in the introduction, early diagnosis of cerebrovascular disease needs CT images with a resolution of 40 $\mu$m, which requires the head motion to be restricted to within 40 $\mu$m during the CT data acquisition. Therefore, efforts must be made to reduce head motions or motion artifacts. However, all the methods in Sec. 1 have limited effects and make it difficult to restrict head motions to within 40 $\mu$m.

In order to obtain in vivo 40-$\mu$m resolution, we proposed to design a new instant CT system. We are planning to use 17 pairs of microfocus x-ray sources and flat-panel detectors. The system will scan and reconstruct the target ROI dozens of times to produce the final high-resolution (40-$\mu$m) images. The instant CT is expected to make in vivo high-resolution CT imaging possible. It may help advance the early diagnosis of some critical illnesses.

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