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Original paper

Assessment of temporal resolution of multi-detector row computed tomography in helical acquisition mode using the impulse method

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ABSTRACT

The purpose of this study was to propose a method for assessing the temporal resolution (TR) of multi-detector row computed tomography (CT) (MDCT) in the helical acquisition mode using temporal impulse signals generated by a metal ball passing through the acquisition plane. An 11-mm diameter metal ball was shot along the central axis at approximately 5 m/s during a helical acquisition, and the temporal sensitivity profile (TSP) was measured from the streak image intensities in the reconstructed helical CT images. To assess the validity, we compared the measured and theoretical TSPs for the 4-channel modes of two MDCT systems. A 64-channel MDCT system was used to compare TSPs and image quality of a motion phantom for the pitch factors P of 0.6, 0.8, 1.0 and 1.2 with a rotation time R of 0.5 s, and for two R/P combinations of 0.5/1.2 and 0.33/0.8. Moreover, the temporal transfer functions (TFs) were calculated from the obtained TSPs. The measured and theoretical TSPs showed perfect agreement. The TSP narrowed with an increase in the pitch factor. The image sharpness of the 0.33/0.8 combination was inferior to that of the 0.5/1.2 combination, despite their almost identical full width at tenth maximum values. The temporal TFs quantitatively confirmed these differences. The TSP results demonstrated that the TR in the helical acquisition mode significantly depended on the pitch factor as well as the rotation time, and the pitch factor and reconstruction algorithm affected the TSP shape.

Introduction

Advances in multi-detector row computed tomography (CT) (MDCT) have resulted in continuous improvements in the temporal resolution (TR) of CT images. In particular, TR is of great interest in cardiac CT. Therefore, many investigators have examined the relations between TR and the image quality of coronary CT images among different generations of MDCT systems [1–5]. There are many studies related to the TR of images generated in the electrocardiogram (ECG)-gated acquisition mode for suppressing cardiac motion artefacts in lung CT images [6–9]. However, the TRs of images obtained in the normal helical acquisition mode, which is routinely used for clinical CT examinations, have not been studied.

In CT examinations using the helical acquisition modes, body movement or breathing during the CT scanning process is sometimes unavoidable, especially in emergencies and infant cases. For such patients, a higher TR is effective in reducing motion artefacts, and it is well known that an increase in rotation speed is an effective means of improving TR. In addition, the pitch factor and the reconstruction algorithm affect TR in the helical acquisition mode because the order and arrangement of the projection data in the multi-detector helical interpolation process noticeably vary with respect to the pitch factor, and the reconstruction algorithm processes these projection data using algorithm-dependent weighting factors for helical interpolation [10–13]. However, since no practical methods have been proposed to measure TR for the helical acquisition mode, the effects of these parameters on it have not been investigated.

Theoretically, TR could be evaluated by examining the temporal sensitivity profile (TSP), similar to how the longitudinal (z-

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directional) spatial resolution can be evaluated using the section sensitivity profile (SSP), which is defined as the impulse response of the CT system along the z-axis [13]. Figure 1 shows examples of theoretical TSP for a step-and-shoot CT image with full (360°) reconstruction and a single-slice helical CT image with 180° linear interpolation (180LI) [14]. In the step-and-shoot CT image, the projection data through a 360° rotation are used with a constant weighting, and thereby its TSP forms a rectangular shape as shown in Fig. 1a. In the single-slice helical CT with 180LI, the TSP forms a triangular shape with a base width equal to the rotation time (Fig. 1b). This corresponds to the triangle weight function for the helical interpolation with its base width equal to the table movement per rotation [13]. These theoretical TSPs can be easily estimated because the weighting functions are already known [14]. In contrast, it is nearly impossible to estimate theoretical TSPs of CT images of recent MDCT systems because the weighting factors are complicatedly processed in their reconstruction algorithms [15,16], and consequently, a special software to correctly reproduce the reconstruction algorithms is needed for the theoretical TSP estimation.

To measure the SSP, a thin Al sheet or a small lead bead is usually employed, which generates an approximation of impulse signals in the z-direction [17,18]. The SSP can then be measured from the reconstructed images with a fine table increment (typically, one-tenth of the nominal slice thickness), which are responses to the approximated impulse signal. According to this principle, a high attenuation object that briefly appears during the helical acquisition is needed to generate a temporal impulse signal for the TSP measurement.

The aim of this study is to propose a practical method for measuring the TSP of MDCT in the helical acquisition mode using a temporal impulse signal generated by a metal ball passing through the acquisition plane. The measurement procedures in the proposed method, the comparisons between theoretical and measured TSPs, and the relationship between the TSP and image quality in a motion phantom are described in this paper.

Materials and methods

Proposed method for the TSP measurement

As shown in Fig. 2, a metal ball was shot along the central rotation axis during helical acquisition at a high speed of approximately 5 m/s to provide almost simultaneous temporal impulse signals to all the detector channels. If the timing difference between the first and last MDCT detector channels is not sufficiently small compared with the width of the TSP, the approximation of the temporal impulse signal becomes insufficient, consequently causing TSP measurement errors. Therefore, the speed of the metal ball was set to be sufficiently high

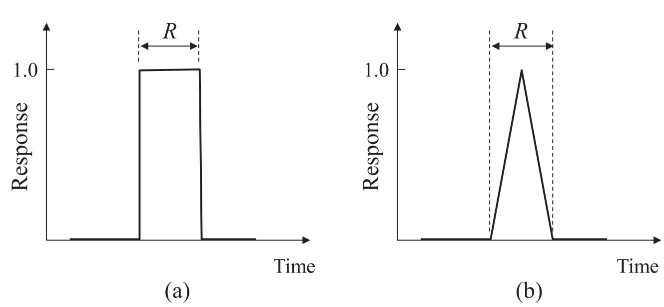

Figure 1. TSPs of (a) a step-and-shoot acquisition image and (b) a single helical acquisition image with 180LI. The base widths of both TSPs are equal to the rotation time *R*.

so that the timing difference was less than one-tenth of the width of the TSP. This is similar to how the thickness of the Al sheet or the diameter of the bead for the SSP measurements were chosen to be less than one-tenth of the full width at half maximum (FWHM) of the SSP [17]. It was assumed that the shortest FWHM of the TSP was 0.1 s for recent MDCTs with detector full widths of 40 mm. Thus, a metal ball speed of approximately 5 m/s, which we used in this study, should be sufficiently high because of the corresponding timing difference of 0.008 s. In most CT systems, it is possible to conduct acquisitions with the patient tables positioned away from the CT gantries. Thus, there was no collision between the patient table and launching platform from which the metal ball was shot.

The passage of the metal ball caused streaks in the reconstructed images, as shown in Fig. 3. Assuming that the table position at time t_0, when the metal ball passed through the acquisition plane, was defined as z_0, the image reconstructed at z_0 showed the maximum intensity of the streak image. As the table speed during the helical acquisition was constant, the difference in z-position between each image and the image at z_0 was proportional to the time difference between them. Therefore, each image had its own time stamp, and consequently, the intensity of its streak image reflected the temporal response to the momentary attenuation caused by the passage of the metal ball through the acquisition plane. Thus, the TSP could be obtained by measuring the mean values of the regions of interest (ROIs) on the streak images within a specified z-position range. The table position (z) could be converted to time (t) to determine the TSP (t) using the following formula:

$$t = \frac{(z - z_0)R}{WP} \tag{1}$$

where R is the rotation time (per 360° rotation), W is the detector full width and P is the pitch factor. The image reconstruction increment should be set small enough (e.g. 0.1 mm) so that the corresponding time increment of the TSP data is short enough to correctly detect the TSP shape. To obtain the normalized response values of the TSP, the background level was subtracted from the ROI values, and then, the resultant values were divided by the maximum ROI value.

Metal ball

We used a metal ball from the popular Japanese gambling machine, Pachinko. The ball was made of steel with the following regulated specifications: 11.0 mm in diameter and 5.4–5.7 g in weight. This product provided high attenuation, a fixed quality level and was large enough for the ROI measurements. An original spring-based mechanism with an adjustable speed setting was developed to shoot the metal ball from a launching platform. After being shot, the guide rail (indicated in Fig. 2) guided the metal ball along the correct trajectory; i.e. aligned with the central axis of rotation of the CT system's gantry. The speed of the metal ball as it passed through the acquisition plane was determined from its average position changes per millisecond observed in high-speed movies with 1000 frames/s, recorded with a high-speed digital camera EX-FC150 (CASIO Computer Company, Tokyo, Japan). The accuracy of the metal ball speed measurement for 10 observations at the 5.0 m/s setting was 5.04 ± 0.11 m/s. Since the free-fall of the metal ball as it passed through the acquisition plane was estimated to be less than 0.4 mm for the 40 mm full width of the detectors, the position change in the vertical (y) direction caused by the free-fall was negligible.

Comparison of measured and theoretical TSPs

We used a 4-channel MDCT system, Somatom Volume Zoom (Somatom VZ; Siemens Medical Solutions, Forchheim, Germany)