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Technical note

Dynamic imaging with dual-source gated Computed Tomography (CT): Implications of motion parameters on image quality for wrist imaging

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ABSTRACT

Objective: Dynamic Computed Tomography (CT) promises insights into the pathophysiology of carpal instability by recording images of the carpus while it is in motion. The purpose of this study was to investigate the effect of motion velocity on image quality for dynamic carpal imaging applications using a clinical dual-source CT (DSCT) scanner.
Methods: A phantom with targets in the axial, coronal and sagittal planes was attached to a motion simulator and imaged using a 64-slice DSCT scanner. Data was acquired when the phantom was stationary and during periodic linear motion. Spatial resolution, motion artifacts and banding artifacts were assessed.
Results: Mean spatial resolution was 0.82 mm at 36 mm/s and 0.79 mm at 18 mm/s. Banding artifacts were mild at 36 mm/s and minimal at 18 mm/s. Motion artifacts were minimal at motion velocity of up to 36 mm/s in both the coronal and sagittal planes. Axial plane motion artifacts were moderate at 36 mm/s and mild at 18 mm/s.
Discussion: Sub-millimeter resolution is achievable with commercially available DSCT scanners with mild to moderate amounts of motion artifacts at velocities of 18 mm/s and 36 mm/s respectively.
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1. Introduction

ECG gated computed tomography (CT) imaging has become a valuable clinical tool for assessing coronary artery disease. In the same way, gated CT imaging can be a valuable tool for dynamic musculoskeletal imaging of small joints such as the wrist. Dynamic musculoskeletal CT imaging was referred to as 4-dimensional (4D) imaging (i.e. 3D + time) in our previous study performed using a single-source CT (SSCT) [1]. The ability to image 3D joint structures during real time motion has always been desirable as it extends the diagnostic capabilities of imaging modalities to include motion abnormalities. Furthermore, in 3D imaging, we can perform a comprehensive evaluation of the wrist motion in 3 directions (flexion-extension, radioulnar deviation, and pronation-supination).

Wrist instabilities can be categorized as dynamic and static. Injuries to the scapholunate interosseous ligament (SLIL), are the most common cause of dynamic wrist instabilities. Patients with such injuries, despite experiencing wrist pain during motion, do not demonstrate any abnormalities on conventional (static) radiographic examinations. With 4D imaging, clinicians may be able to diagnose these conditions more effectively.

For a complex joint such as the wrist which exhibits 6 degrees of freedom in motion, dynamic wrist CT imaging has far-ranging implications. In recent years, studies carried out by Carelson B et al. and Founami M et al. [2,3], have demonstrated the feasibility in performing in vivo dynamic studies of the carpus. In both studies, the authors performed 4D imaging of the wrists using rotational X-ray (4D-RX) imaging system. However, this approach has its drawbacks. In 4D-RX imaging, the joint has to be moved through many cycles of motion, to acquire 4D images, as compared to using CT.

In addition to a better understanding of wrist kinematics, the long-term objective of this study is to address the

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clinical problem of diagnosing dynamic carpal instabilities. Current methods for imaging carpal motion are limited to either two-dimensional (2D) video fluoroscopy, or step-and-shoot series of static three-dimensional (3D) computed tomography scans. However, recent developments and studies using 4D imaging as a diagnostic approach have been promising. A recent statistical study by Giessen et al. [4] was developed to detect wrist abnormalities based on statistical model of wrist motion pattern and bone shape, and this study was performed using 4D-RX system.

In another study by Berdia et al. [5], it was found that carpal bones exhibit hysteresis during wrist motion which was observed in the difference in carpal motion path of a normal bi-directional wrist motion. This means that the instantaneous position of carpal bones is not only dependent on the position of the wrist but also on the direction in which the motion is occurring. Hence, step-and-shoot methods of imaging will not be able to detect and measure this hysteresis effect - the magnitude of which may be used to quantify carpal instability patterns.

For this study, in order for the motion pattern of the geometric phantom to be similar to the wrist motion, the motion amplitudes between 5 mm to 20 mm were chosen. This is based on the largest motion amplitude within the proximal carpal row, during radioulnar deviation (20° ulnar deviation to 10° radial deviation), which occurs at the distal scaphoid and averages 12.4 mm [6].

The feasibility of 4D CT imaging was first shown in our previous study by Tay et al. [1] using a 64-slice SSCT scanner with a temporal resolution of 165 ms. However, it required factory modifications of the scanner to perform scans at a table speed slower than in the commercially available protocols, i.e. with a pitch of 0.1. This study used a 64-slice dual source computed tomography (DSCT) scanner (SOMATOM Definition by Siemens Healthcare, Forchheim, Germany) which has an improved temporal resolution of 83 ms [7]. This promises equivalent dynamic image quality without requiring any modifications to the scanning pitch parameter. The purpose of this study is to assess the quality of 4D CT images of a periodically moving geometric phantom in a DSCT scanner with a clinical scan protocol at a pitch of 0.2.

2. Materials and methods

2.1. Equipment set-up

A 64-slice DSCT scanner (SOMATOM Definition, Siemens Healthcare, Forchheim, Germany) was used to acquire all images with a retrospectively gated CT protocol at 0.2 pitch value, 60 mAs/rot, 120 kV and 0.33 s rotation time. A geometric spatial resolution phantom (QRM, Möhrendorf, Germany) with resolution targets in the axial (x–y), coronal (x–z) and sagittal (y–z) planes was mounted onto a linear slider on a custom made motion platform powered by a servo motor (Mitsubishi Electric Corporation, Tokyo, Japan) (Fig. 1).

The phantom was set in periodic linear motion along the x-axis slider by the servo motor system, which was controlled using TwinCAT I/O real time driver software (Beckhoff Automation GmbH, Verl, Germany). A customized data logging software was used to record the instantaneous velocities of the moving phantom (data was sampled every 0.12 s) with respect to its corresponding displacement on the x-axis slider (Fig. 1). The motion profile presented was chosen to give the maximum duration of time at a known constant velocity.

A simulated electrocardiogram (ECG) signal in the form of a 10 ms voltage spike was generated at the end of each motion cycle to simulate the R wave of the QRS complex typically seen in a cardiac cycle.

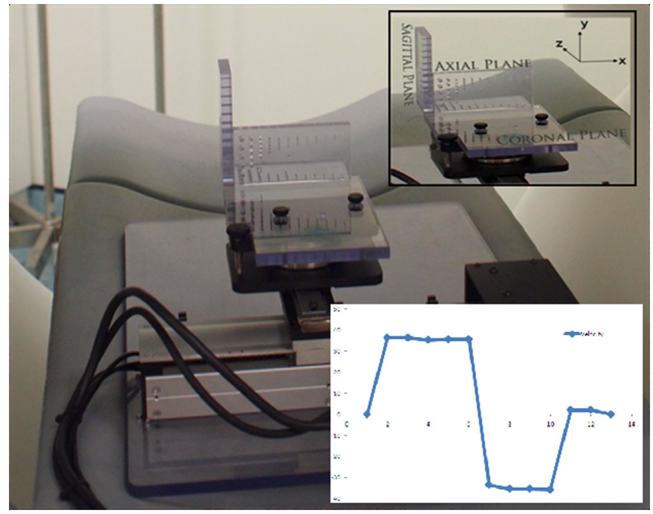

Fig. 1. High-resolution phantom with targets at three planes. (Inset (Top): Orientation of the axial, sagittal and coronal planes. Inset (Bottom): A typical instantaneous velocity of moving phantom over one motion period of 1.5 s).

Data were acquired while the phantom was at rest (using the ECG signal simulated by the CT system for a spiral static protocol) and during periodic linear motion along the x-axis at a frequency of 40 cpm with amplitudes ranging from 5 mm to 20 mm. The corresponding maximum instantaneous velocities (hereafter termed "velocities") of the phantom moving at a frequency of 40 cpm with amplitudes of 5 mm to 20 mm along the x-axis are shown in Table 1.

In addition to this, the motion frequency was calculated based on Ohnesorge et al. study [8], where the maximum pitch value is given by

$$\text{pitch} \leq \frac{M-1}{M}\frac{T_{rot}}{T_p} \tag{1}$$

where M is the number of detector rows used in the gated mode. Hence, for 0.2 pitch value, using Eq. (1), the minimum motion frequency is 37.5 cpm. Thus, the motion frequency of 40 cpm was selected to satisfy the minimum frequency requirement for a scan at pitch value of 0.2 to avoid image interpolation errors [8,9].

2.2. Image reconstruction

For each scan, data sets were reconstructed at every one tenth of a period (10 ECG phases) with a slice width of 0.6 mm, 0.6 mm reconstruction increment, 200 mm field of view, 512 × 512 pixel and medium-sharp reconstruction kernel (B46f). The number of phases chosen was sufficient for this study, as we were able to reconstruct a smooth 3D "movie" running at around 7 frames per second (fps).

2.3. Image assessment

The acrylic 3D spatial resolution phantom (QRM-3DSR-02, Moehrendorf, Germany) used in this study is made up with a series of drilled holes with varying diameter and spacing from 0.4 mm to 4.0 mm, allowing for an order of magnitude in spatial frequency. As the holes within the phantom move along the x-axis, projections acquired at different angular positions "see" the holes at different locations along the axis.

The image slice corresponding to the middle of each resolution target was used to assess spatial resolution and image artifacts. Quantitative measurements were performed using Analyze 8.1 software (Mayo Foundation for Medical Education and Research, Rochester, MN).

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