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Understanding the Relationship Between Image Quality and Motion Velocity in Gated Computed Tomography: Preliminary Work for 4-Dimensional Musculoskeletal Imaging

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Abstract

Objectives—To study the effect of motion velocity on image quality to determine the requirements for 4-dimensional (4D; ie, 3D + time) musculoskeletal computed tomographic (CT) imaging.

Materials and Methods—A phantom with resolution targets in both axial (x - y) and coronal (x - z) planes was attached to a motion device and scanned with 64-slice CT using a retrospectively gated CT protocol with pitch values of 0.1 and 0.2. Data were acquired with the phantom at rest and while moving periodically along the x axis at several velocities. Spatial resolution and motion artifacts were assessed both for the axial and coronal targets.

Results—A linear relationship was found between motion artifact severity and phantom velocity. Spatial resolution was better preserved in the coronal target. However, coronal images displayed banding artifacts, with band displacements being linearly related to motion velocity.

Conclusions—The 4D CT imaging of periodically moving objects with velocities up to 20 mm/s is feasible using a pitch value of 0.1 and a motion frequency of 30 cycles per minute.

Keywords

64-slice computed tomography; 4D imaging, motion artifacts; ECG gating

Cardiac gated multidetector-row computed tomography (MDCT) has become a valuable clinical tool for assessing coronary artery disease.¹ A potential noncardiac application of gated MDCT could lie in real-time imaging of small joints (eg, carpal joints in the wrist). Four-dimensional (4D) musculoskeletal imaging of the joint (ie, real-time imaging during joint motion) may provide novel insights into the pathophysiology of joint instability. Some investigators have shown that the carpal bones of the wrist joint demonstrate hysteresis that is dependent on the direction of wrist motion.² For instance, the amount that the scaphoid or lunate bone flexes at a particular wrist position differs depending on the direction the wrist was moved to get to that position. It is suggested that the diagnosis of dynamic instabilities may

rest on the ability to detect abnormal hysteresis during continuous joint motion.² Clearly, 4D imaging is the logical means to detect such dynamic joint instabilities.³

Current imaging of joint motion is limited to either 2D video fluoroscopy or to “quasi-motion” from a series of static 3D images. We are aware of only 1 study that described true 4D (dynamic 3D) imaging of the wrist.⁴ This study used a technique that is based on a rotational x-ray (C-arm) system and has some disadvantages compared with 4D imaging using gated MDCT.⁵

Unlike heart rate, which is an important factor in cardiac gated MDCT, the frequency and velocity of joint motion is largely under a person's volitional control. Therefore, imaging slow and periodic joint motion using retrospectively gated CT may be feasible.

Image quality depends on object displacement during the time it takes to acquire all projections necessary for image reconstruction (this time is known as temporal resolution). For real-time imaging of joint kinematics, the limiting parameter is not heart rate, but rather maximum velocity, which is a function of motion amplitude and frequency. In this article, we study the effect of motion velocity on spatial resolution and motion artifacts using a CT resolution phantom to determine the requirements for 4D (ie, 3D + time) CT imaging of periodically moving objects.

The study was performed using a 64-slice CT scanner with a 0.33-second gantry rotation time as it had a significantly better temporal resolution (165 milliseconds) compared with the earlier generations of MDCT scanners (eg, a 4-slice CT scanner had temporal resolution of 250 milliseconds).

MATERIALS AND METHODS

A high-contrast spatial resolution phantom (QRM, Möhrendorf, Germany) with resolution targets in the axial (x - y) and coronal (x - z) planes was mounted on a Daedal crossed roller linear slide (Parker Hannifin Corporation, Rohnert Park, Calif) as shown in Figure 1. A periodic linear motion of the resolution phantom was achieved with an Si5580 step motor drive (Applied Motion Products, Watsonville, Calif) that was controlled with a laptop computer using Si Programmer V2.5.7 software. A simple trapezoidal velocity versus time profile was used, where the duration of the maximum velocity “plateau” was kept constant by adjusting the magnitudes of acceleration and deceleration. By keeping the duration of the “plateau” constant, the number of phases corresponding to the maximum velocity (ie, most affected by motion) was kept constant. An electronic trigger within the program provided a small 10-millisecond voltage spike at the end of each motion cycle to provide the synchronization (“electrocardiogram” [ECG]) signal required for gated scanning. The motion device with the attached resolution phantom was positioned in the gantry with its motion axis aligned along the x axis (the horizontal axis in the transaxial plane) and scanned on a 64-slice CT scanner (Sensation 64, Siemens Medical Solutions, Forchheim, Germany) using a retrospectively gated CT protocol with 0.1 and 0.2 pitch values and 0.33 seconds of rotation time. The use of 32×0.6 mm collimation and a z -flying focal spot technique⁶ resulted in 64 overlapping projections per rotation. Data were acquired while the phantom was at rest (using ECG signal simulated by the CT system) and during periodic linear motion along the x axis at maximum velocities of 5, 10, 15, 20, 25, 30, and 40 mm/s.

The frequency of motion was fixed at 30 cycles per minute (cpm) for the pitch value of 0.1 and 38 cpm for the pitch value of 0.2. This selection satisfied the criterion between frequency and pitch that must be met to allow all phases of the moving object to be “seen” by some portion of the detector at any z axis location. Pitch is defined as the ratio of table increment per gantry rotation to total nominal beam width, W (pitch = $V \cdot T_{\text{rot}} / W$, where V is table speed, T_{rot} is gantry rotation time). That is, the table should not move more than W during the time of 1 motion

cycle, T (ie, $V \leq W/T$), to avoid gaps in coverage along the z axis. According to Ohnesorge et al,⁷ the maximum pitch value is given by

$$\text{pitch} \leq \frac{M-1}{M} \frac{T_{\text{rot}}}{T_p} \quad (1)$$

where M is the number of detector rows used in the gated mode. For the 0.2 pitch value, which is a standard pitch for ECG-gated protocols on Sensation-64, equation (1) gives a maximum motion period of 1.65 seconds and a corresponding minimum motion frequency of 37.5 cpm. In our experiments with the 0.2 pitch value, we used 38 cpm of motion frequency to allow for a small margin of tolerance.

Having a concern that the 1.65-second period did not provide a sufficiently slow motion velocity, we implemented the 0.1 pitch value using factory assistance, as this option is not commercially available. According to equation (1), the 0.1 pitch value allows a maximum motion period of 3.2 seconds and a minimum motion frequency of 18.8 cpm. Unfortunately, the ECG detection algorithm on the CT system does not allow scanning with a heart rate less than 27 cpm. Therefore, in our experiments with the 0.1 pitch value, we used a motion frequency of 30 cpm.

For each scan, both axial and coronal data sets were reconstructed at 10 ECG phases (10 time points within the motion cycle) with a slice width of 0.6 mm, 0.6-mm reconstruction increment, 200-mm field of view, and sharp reconstruction kernel (B70). The images corresponding to the center of each resolution target were used to assess spatial resolution and image artifacts. Quantitative measurements were performed using Analyze 7.0 software (Mayo Foundation for Medical Education and Research, Rochester, MN).

Spatial resolution was quantified by the minimum diameter of holes that could be resolved on axial and coronal images of the corresponding resolution targets. All 10 phases of motion were assessed, and the average spatial resolution was calculated.

Band artifacts⁸ observed in images of the coronal resolution target (ie, x - z plane) were quantified by measuring the maximum displacement found between bands using the line profile tool in Analyze 7.0 (Fig. 2).

Motion artifacts observed in the axial and coronal resolution targets had different appearances and thus were assessed using different methods. The motion artifacts in the axial target were scored on a 4-point scale as shown in Figure 3: none (0), no motion artifacts; mild (1), some artifacts present but the 4-mm holes remain circular without any significant distortion and the edges of the resolution target remain intact; moderate (2), distortion of the 4-mm holes, which can still be individually resolved, with some minor distortions of the edges and corners of the resolution target; severe (3), motion artifacts affecting both the leading and trailing edges of the resolution target and complete distortion of the 4-mm holes.

Motion artifacts in the coronal target were objectively quantified by measuring the maximum length of shading artifact along the x axis at the edge of the coronal target (Fig. 4). This was done by using the intensity profile in line profile tool in Analyze 7.0. The total number of bands affected by motion in each coronal image was also recorded. After measuring all the affected bands, the average over all phases was calculated for each velocity condition. We considered coronal motion artifacts as mild if the mean length of edge shading was less than 3 mm, moderate if the mean length of edge shading was 3 to 6 mm, and severe if the mean length of edge shading was more than 6 mm. For motion artifact assessment, all 10 phases were assessed, and the mean was calculated separately for the axial and coronal targets.

RESULTS

Spatial Resolution

The minimum diameter of holes that could be resolved in the axial resolution target of the moving phantom averaged for 10 phases is shown in the Table 1. The background of some of the axial images demonstrated subtle high-frequency artifacts^{6,9} caused by the sharp reconstruction kernel, but they did not affect the image quality or the assessment of spatial resolution (Fig. 5).

In the coronal resolution target, motion had a lesser effect on spatial resolution and the 0.6-mm diameter holes were resolved from rest up to speeds of 40 mm/s (see Fig. 6 and Table 1).

Band Artifacts

The coronal images of the moving phantom showed band artifacts, with the maximum band shift along the x axis being linearly related to the phantom velocity (maximum band shift = $0.13 \times \text{velocity}$, $P < 0.0001$) (Fig. 7). The band thickness along the z axis was essentially equal to the distance traveled by the table in 1 motion cycle, and hence, depended on pitch and motion frequency (Fig. 8). For $32 \times 0.6 = 19.2$ mm of detector collimation and 0.33 seconds of rotation time, 0.1 and 0.2 pitch values corresponded to the table speed of 5.8 and 11.6 mm/s, respectively. At the pitch value of 0.1 and motion frequency of 30 cpm, the distance traveled by the table in 1 motion cycle was $5.8 \text{ mm/s} \times 2 \text{ s} = 11.6 \text{ mm}$. At the pitch value of 0.2 and 38 cpm, the corresponding distance was $11.6 \text{ mm/s} \times 1.58 \text{ s} = 18.4 \text{ mm}$. The results of actual band thickness measurements (11.7 mm and 18.8 mm, respectively) were in excellent agreement with these estimates.

Motion Artifacts

The motion artifact score (averaged for 10 phases) for the axial resolution target was 0.7 (none to mild) for a phantom velocity of 10 mm/s, 1.7 (mild to moderate) for 20 mm/s, and 2.0 (moderate) for 40 mm/s (Fig. 9). At 10 mm/s, 80% of the phases had none or mild motion artifacts. At 20 mm/s, 40% of the phases had none or mild motion artifacts. At 40 mm/s, none of the phases were free from motion artifacts. An approximately linear relationship between the average motion artifact score and the phantom velocity was observed (axial motion artifact score = $0.06 \times \text{velocity}$, $P < 0.0001$).

In the coronal resolution target, motion artifacts were classified as mild (mean length of edge shading of 1.5 mm) at 10 mm/s, moderate (mean length of edge shading of 3.6 mm) at 20 mm/s, and severe (mean length of edge shading of 7.5 mm) at 40 mm/s. A linear dependence between the average motion artifact score and the phantom velocity was observed (coronal motion artifact score = $0.17 \times \text{velocity}$, $P < 0.0001$) (Fig. 10).

DISCUSSION

Our study using a moving CT resolution phantom has shown an approximately linear relationship between the degree of image quality degradation and motion velocity (Figs. 9-10). The severity of motion artifacts was mild or moderate for a motion velocity of less than or equal to 20 mm/s.

High-contrast spatial resolution of 0.6 mm was preserved up to motion speeds of 40 mm/s in the coronal target, whereas in the axial target, significant degradation of spatial resolution occurred when the motion speed exceeded 20 mm/s. The much better preservation of high-contrast spatial resolution in the coronal target compared with the axial target was quite surprising. This can be understood by considering which projections contribute information to

the image that distinguishes the holes from the surrounding background material. The holes in the axial (x - y plane) resolution target have their symmetry axes along the z axis. In this case, all projections used in the partial scan reconstruction contribute to the image with a relatively equal weight. 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 x axis. This results in image blurring and arc-type motion artifacts, which cause a significant degradation of spatial resolution.

The holes in the coronal (x - z plane) resolution target, however, have their symmetry axes along the y axis. In this case, projection data acquired at different angular positions vary considerably. The projections nearly parallel to the y axis go either through the holes (no attenuation) or through the phantom, resulting in a large signal difference. Alternately, the projections nearly parallel to the x axis go through the phantom perpendicular to the holes, resulting in very little signal differences between the ray sums that pass through a hole and those that do not. Hence, the projections nearly parallel to the y axis contribute almost all of the differentiating information to the image and form a relatively sharp (snapshot) image because such projections happen during a very short time interval. The rest of the projection data, which carries very little information about the holes, results in a relatively uniform appearance, regardless of the phantom position and, hence, does not cause substantial blurring or artifacts.

Despite better spatial resolution in the coronal target in our motion phantom study, coronal images displayed banding artifacts, where the neighboring bands corresponding to 2 consecutive motion cycles were shifted with respect to each other along the x axis (axis of motion). Most likely, this artifact was caused by an asynchrony between the gating signal produced by our phantom controller and the actual periodic motion of the phantom. Because the maximum band shift increased linearly with the velocity (Fig. 7), with an average shift of approximately 2 mm at 20 mm/s, we estimated the asynchrony on the order of 0.1 second. This is consistent with our observation that despite the motion cycle being programmed to be exactly 2 seconds, the motion frequency recognized by the scanner was 28 cpm, indicating the motion cycle of 2.14 seconds.

Even if the asynchrony causing banding artifacts in our phantom study could be completely removed, a real study of moving small joints is bound to have banding artifacts because volitional wrist motion will not likely be perfectly periodic. Fortunately, band displacements can be manually corrected with retrospective editing of the ECG signal by an experienced CT technologist, provided that a clear object contour is visible to assist with realignment.

The band thickness and, hence, the total number of bands in images of the coronal target depend on pitch and motion frequency. In these images, some bands appeared more affected by motion than others, although degradation of image quality in the axial target was relatively uniform. We believe that this effect is caused by the partial reconstruction technique. For the axial target, the entire image is reconstructed from the data collected from a single gantry rotation and, hence, affected by motion in a relatively uniform fashion. On the contrary, images of the coronal target are composed of bands, with each band being reconstructed from the data collected at different gantry rotations and different motion cycles (but the same phase). However, the degree of motion degradation depends on the orientation of the partial reconstruction source trajectory with respect to the direction of motion. This variation in the degree of motion degradation is reflected in the images of the coronal target.

Because modern 64-slice CT scanners acquire data with approximately isotropic spatial resolution, high-quality multiplanar reconstruction images can be obtained not only in the coronal plane, but also in the sagittal plane. We did not assess the sagittal plane because of the design of our phantom and the fact that there was no motion occurring within the sagittal plane

(ie, along the y or z axis). Although it is possible to redesign the phantom so it would move in the sagittal plane, we believe that under such motion, the degradation of spatial resolution in the sagittal plane would be similar to that in the coronal plane. In the study of actual joint motion, all 3 reconstruction planes (axial, coronal, and sagittal) can be useful.

This interdisciplinary work was conducted in close collaboration with experts in orthopedic hand surgery and radiology. It is the first investigation of the potential of using ECG-gated CT for noncardiac 4D imaging. It is preliminary in nature, and 1 limitation is that only linear motion along the x axis was investigated, whereas musculoskeletal joint motion is largely rotational in nature. However, rotational joint motion can be decomposed into finite linear motions along the x , y , and z axes. In wrist radioulnar deviation, the capitate bone undergoes in-plane rotation in the x - z coronal plane and out-of-plane rotation in the y - z sagittal plane, with an axis of motion situated within its head.¹⁰ However, the out-of-plane rotation and the z component of linear motion for in-plane rotation is very small. The most significant linear component of motion is in the x axis. For this reason, we focused our study on linear motion along the x axis. Although further studies could be performed with linear and rotational motion in other axes to study their effects on image quality, we felt that this study provides sufficient information for us to proceed with studies using cadaveric specimens.⁵

CONCLUSION

Using the 64-slice MDCT technology, we have determined the boundary conditions suitable for time-resolved imaging of slowly moving joints. For small joints performing periodic motion predominantly along the x axis, 4D CT imaging is feasible if the maximum object velocity does not exceed 20 mm/s. Using a pitch value of 0.1 and a motion frequency of 30 cpm, high-contrast spatial resolution of 0.8 mm or better in both axial and coronal planes can be expected for motion ranges up to 20 mm. We estimate that even during maximal radioulnar deviation, when the hand deviates an angular arc of 40 degrees, the largest motion range in the carpal joint does not exceed 16 mm (distal scaphoid bone). Based on our current protocol, the average motion velocity of carpal bones within the wrist would not be expected to exceed 20 mm/s during 4D imaging. Thus, 4D CT imaging of slow and periodic motion of carpal joints seems feasible using commercially available retrospectively gated CT techniques.

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REFERENCES

1. Schoepf UJ, Becker CR, Ohnesorge BM, et al. CT of coronary artery disease. *Radiology* 2004;232:18–37. [PubMed: 15220491]
2. Berdia S, Short WH, Werner FW, et al. The hysteresis effect in carpal kinematics. *J Hand Surg [Am]* 2006;31:594–600.
3. Watson HK, Weinzeig J, Zeppieri J. The natural progression of scaphoid instability. *Hand Clin* 1997;13:39–49. [PubMed: 9048182]
4. Carelsen B, Bakker NH, Strackee SD, et al. 4D rotational x-ray imaging of wrist joint dynamic motion. *Med Phys* 2005;32:2771–2776. [PubMed: 16266090]
5. Tay SC, Primak AN, Fletcher JG, et al. Four-dimensional computed tomographic imaging in the wrist: proof of feasibility in a cadaveric model. *Skeletal Radiol* 2007;36:1163–1169. [PubMed: 17805530]

6. Flohr TG, Stierstorfer K, Ulzheimer S, et al. Image reconstruction and image quality evaluation for a 64-slice CT scanner with z-flying focal spot. *Med Phys* 2005;32:2536–2547. [PubMed: 16193784]
7. Ohnesorge B, Flohr T, Becker C, et al. Cardiac imaging by means of electrocardiographically gated multisection spiral CT: initial experience. *Radiology* 2000;217:564–571. [PubMed: 11058661]
8. Taguchi K, Chiang BS, Hein IA. Direct cone-beam cardiac reconstruction algorithm with cardiac banding artifact correction. *Med Phys* 2006;33:521–539. [PubMed: 16532960]
9. Kyriakou Y, Kachelriebe M, Knaup M, et al. Impact of the z-flying focal spot on resolution and artifact behavior for a 64-slice spiral CT scanner. *Eur Radiol* 2006;16:1206–1215. [PubMed: 16541229]
10. Kaufmann R, Pfaeffle J, Blankenhorn B, et al. Kinematics of the midcarpal and radiocarpal joints in radioulnar deviation: an in vitro study. *J Hand Surg [Am]* 2005;30:937–942.

FIGURE 1.
The high-contrast CT resolution phantom with axial and coronal targets attached to a precision linear motion slide driven by a computer-controlled step motor.

FIGURE 2.

To quantitate band artifacts, the maximum shift between the bands (distance between points E and F) was measured using calipers in the line profile tool of the Analyze program.

FIGURE 3.

Motion artifacts in images of the axial target, when present, uniformly affected the entire image. Axial motion artifacts were scored on a 4-point scale, as described in Materials and Methods.

FIGURE 4.

Because of motion blur, the CT numbers along the x axis do not immediately drop from the acrylic value (100 Hounsfield units [HU]) to the air value (-1000 HU) but gradually decrease over some distance causing a shading artifact. This distance (between 2 arrows) was measured by counting the number of voxels with CT values in the range of 0 to -900 HU and multiplying it by the known voxel size. Not all bands were equally affected by motion (see Discussion).

*Noticeably affected bands.

FIGURE 5.

Images of the axial resolution target at rest and at 20 mm/s. As shown in the inserts, all five 0.6-mm holes can be resolved in the stationary target, whereas the spatial resolution of the moving target is degraded by motion, and only 0.7-mm holes can be resolved. V indicates velocity.

FIGURE 6.

Images of the coronal resolution target at rest and at 40 mm/s. As shown in the inserts, all five 0.6-mm holes can be resolved not only in the stationary phantom, but also in the moving target. Therefore, despite the presence of shading and band artifacts, the high-contrast spatial resolution of the coronal target remains preserved at 0.6 mm up to speeds of 40 mm/s (see Discussion).

FIGURE 7.

The band shift along the x axis of band artifacts has shown approximately linear dependence with the phantom velocity. Up to 20 mm/s, the amount of displacement is relatively small. Beyond 20 mm/s, it increases to more than 3 mm.

FIGURE 8.

The thickness of the band artifacts (as measured along the z axis) is a function of the table speed (pitch) and the motion period. Essentially, it is a reflection of the distance moved by the table during 1 motion period.

FIGURE 9.

Mean motion artifact score for the axial target versus the maximum phantom velocity. An approximately linear relationship can be seen up to speed of 40 mm/s.

FIGURE 10.

Mean motion artifact score for the coronal target, obtained by measuring the maximum length of shading artifact at the edge of the coronal target, versus the maximum phantom velocity.

TABLE 1
Mean Image Spatial Resolution as a Function of Motion Velocity

Velocity (mm/s)	0	5	10	15	20	25	30	40
Axial spatial resolution (mm)	0.63	0.64	0.68	0.71	0.8	0.82	0.89	0.91
Coronal spatial resolution (mm)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6