Electrocardiographically Gated 16-Section CT of the Thorax: Cardiac Motion Suppression

Thirty patients underwent 16-section multi-detector row computed tomographic (CT) angiography of the thorax with retrospective electrocardiographic gating. Institutional review board approval was obtained for retrospective analysis of CT scan data and records; patient informed consent was not required. Images reconstructed at six different time points (0%, 20%, 40%, 50%, 60%, 80%) within the R-R interval on the electrocardiogram were analyzed by two radiologists for diagnostic quality, to identify suitable reconstruction intervals for optimal suppression of cardiac motion. Five regions of interest (left coronary artery, aortic root, ascending and descending aorta, pulmonary arteries) were evaluated. Best image quality was achieved by referencing image reconstruction to mid-diastole (50%–60%) for the left coronary artery, aortic root, and ascending aorta. The pulmonary arteries are best displayed during mid- to late diastole (80%).

Cardiac motion artifacts degrade the diagnostic quality of thoracic cardiovascular computed tomographic (CT) images. Some of these artifacts (eg, motion artifacts that mimic aortic dissection) are recognized as important sources of potential diagnostic error (1,2). Synchronization of the CT acquisition with the patient’s electrocardiogram (ECG) reduces cardiac motion artifacts and enables noninvasive visualization of the coronary arteries (3,4) and other cardiac anatomy (5,6). ECG synchronization also has been shown to improve image quality at CT imaging of noncardiac thoracic structures (7–9).

Retrospective ECG gating (10) is the most commonly used strategy for ECG synchronization at multi-detector row CT. Substantial effort has been invested in defining suitable time points during the cardiac cycle for reconstruction of CT data to provide optimal depiction of the coronary arteries (11–13). It has been shown that retrospective ECG gating can be beneficially employed for reducing transmitted cardiac pulsation also in more extensive scanning volumes in the thorax (9,14). However, the through-plane spatial resolution that could be achieved with the retrospective ECG gating technique by using the previous generation of four-section multi-detector row CT scanners was limited by the relatively long scanning duration inherent in data oversampling. Thus, high-resolution acquisition could be achieved only for relatively small volumes—for example, the coronary arterial tree—but not for extended coverage of the entire chest. The advent of multi-detector row CT scanners with 16 or more detector rows effectively has eliminated these limitations and enables scanning of the entire thorax with retrospective ECG gating and submillimeter (ie, 0.50–0.75-mm, depending on scanner type) through-plane resolution in a single breath hold (15). Thus, the purpose of our study was to identify ECG-referenced image reconstruction intervals for suppressing cardiac motion at high-resolution 16-section CT angiography in the thorax.

Materials and Methods

Study Design

This study was performed with institutional review board approval for retrospective analysis of CT data and records of patients undergoing retrospectively...
ECG-gated multi–detector row CT; informed patient consent was not required.

Our study included 30 consecutive patients who were examined with retrospectively ECG-gated 16-section multi–detector row CT angiography between August and December 2002 for clinical reasons. The 30 patients had undergone scanning for suspected pulmonary embolism (n = 24) or dissection of the thoracic aorta (n = 4) or for assessment of coronary artery bypass graft patency (n = 2). The patient population consisted of 12 men and 18 women with an age range of 31–88 years (mean, 56.0 years). The age range of women was 36–88 years (mean, 57.7 years), and that of men was 31–76 years (mean, 57.8 years).

Image Acquisition

Scanning was performed with a spiral multi–detector row CT scanner (Somatom Sensation 16; Siemens Medical Solutions, Forchheim, Germany) with 16 detector arrays. The scanner is capable of retrospective ECG gating with three chest leads. Retrospective ECG gating entails recording the patient’s digital ECG tracing simultaneously with CT data acquisition as a prerequisite for image reconstruction based on data acquired at an optimal phase of the cardiac cycle. Acquisition was performed in the caudocranial direction with 420-msec rotation time, 12 × 0.75-mm beam collimation, and a pitch of 0.31. Studies were contrast enhanced with an intravenous bolus injection of 120 mL of iopromide containing 300 mg of iodine per milliliter (Ultravist; Berlex Laboratories, Wayne, NJ) at an injection rate of 3–4 mL/sec.

Image reconstruction was performed with a 0.75-mm section thickness and a 0.50-mm reconstruction increment by using a soft vascular kernel suitable for multi–detector row CT angiography. No β-blockers were used to lower the patient’s natural heart rate. If the heart rate was faster than 71 beats per minute, segmented CT data from two consecutive heart cycles were used for reconstruction of individual transverse images (15). Data from six time points (0%, 20%, 40%, 50%, 60%, and 80% of the R-R interval) were used for retrospective image reconstruction encompassing the entire cardiac cycle, from the onset of the R wave (0%) to late diastole (at approximately 80% of the R-R interval). The heart rate of each patient and the presence or absence of cardiac arrhythmia were recorded by using information from the stored digital ECG tracing. The CT scanning time in seconds and the scanning range in millimeters were also recorded for each patient, in accordance with Digital Imaging and Communications in Medicine standards.

Image Analysis

Five anatomic areas were evaluated: aortic valve, ascending and descending thoracic aorta, left coronary artery, and para-cardiac pulmonary vessels. Image data for all patients at all six reconstruction time points were viewed at a commercially available workstation for two- and three-dimensional display of cross-sectional medical images (3D Plug ‘n View; Voxar, Framingham, Mass) and were evaluated with consensus by two experienced chest radiologists (U.J.S. and P.C., with 8 and 20 years of experience, respectively, in reading chest CT images). Reconstructions of CT data from different time points in the cardiac cycle in each patient were presented together and in random.
order. Readers were blinded to patient identity and clinical information and to the reconstruction time point used. The radiologists rated each region of interest in all reconstructed data sets by using a five-point ordinal rating scale with integers ranging from 1 to 5 to define image quality as follows: 5, no motion artifacts, perfect image quality; 4, minimal motion artifacts, between no and moderate motion artifacts; 3, moderate motion artifacts, image still diagnostic; 2, severe motion artifacts, limited diagnostic value; 1, severe motion artifacts, no diagnosis possible (9). These general categories were adapted to the specific requirements for diagnostic imaging of each organ system. To define image quality for visualization of the left coronary artery at the different image reconstruction time points, the course of the vessel was analyzed for motion artifacts from its origin to the bifurcation and distal segments of the left anterior descending coronary artery. Image quality was graded as optimal if the entire length of the vessel could be traced without disruption by motion artifacts, enabling exclusion of significant stenotic disease. The image quality for visualization of the aortic root was the demarcation of the aortic orifice, aortic valve annulus, and valvular cusps. In a similar fashion, the ascending and descending aorta were assessed for doubling of anatomic structures and for stair-step artifacts attributable to transmitted cardiac pulsation. The vessels of the pulmonary circulation were analyzed for transmitted cardiac pulsation artifacts causing discontinuity of vessels, doubling of vascular structures, or the “twinkling star” artifact (16). The depiction of smaller pulmonary arteries in the vicinity of the heart, and especially their clear and undisrupted delineation, was used as a criterion for determining diagnostic quality. Images were considered to be of diagnostic quality at a score of 3.0 or above. Transverse section scroll-through mode, multiplanar reformation, maximum intensity projection, and three-dimensional volume rendering were available for image display and analysis and were used at the viewers’ discretion.

Statistical Analysis

For each reconstruction time point and each anatomic area, we computed the means and standard deviations of 30 individual image ratings. As a sample size of 30 is ordinarily considered fairly large (17), a power analysis was not performed. Normality of the sample was assumed but was not specifically tested. Instead of analyzing discrete data, we assumed that the distribution of the scores was Gaussian. Thus, sequential paired Student t tests were conducted to test for difference in mean score between two adjacent time points. The optimal range of time points was recorded, and corresponding P values were calculated for difference in ratings between time points and ranges.

Results

The mean patient heart rate was 80 beats per minute (range, 44–128 beats per minute). Two patients had cardiac arrhythmia. The mean scanning range was 238 mm (range, 180–308 mm). The average time needed for scanning of the entire thorax, from the diaphragm to the apex of the lung, was 37 seconds (range, 21.6–47.3 seconds).

The two readers in consensus evaluated six retrospectively ECG-synchronized image data sets for each of the 30 patients (180 data sets). In each of these data sets, five anatomic areas were rated for quality of depiction, resulting in 30 ratings per patient (900 ratings).

The mean ratings for image quality at the six different reconstruction time points in all 30 patients are graphically displayed in Figure 1. The image quality for the left coronary artery (Figs 2, 3) was...
rated best when reconstruction was retrospectively referenced to 50% or 60% of the R-R interval on the ECG tracing. At these time points, mean scores were 3.17 (± 0.75) and 3.21 (± 0.87), respectively. No statistically significant difference was found between the scores for images reconstructed from CT data acquired at 50% of the R-R interval and those reconstructed from data acquired at 60% of the R-R interval; the scores for these two time points, however, were significantly better (P < .001) compared with those for images reconstructed from data acquired at other phases of the cardiac cycle.

Similarly, image quality for the aortic root (Figs 4, 5) was also rated best with reconstruction of image data from 50% or 60% of the R-R interval. For these time points, average scores were 3.32 (± 0.79) and 3.25 (± 0.70), respectively. Again, there was no statistically significant difference in the image quality scores between these two reconstruction time points; however, the quality of images reconstructed from data acquired at these time points was significantly superior to that of reconstructions from data at 40% (P = .005) and at 80% (P = .01) of the R-R interval.

When results for the ascending aorta were compared, quality scores likewise did not differ significantly between images obtained from data at 50% and those obtained from data at 60% of the R-R interval, but quality was significantly better for images reconstructed from data at these time points compared with quality for images reconstructed from data at 40% (P = .02) or 80% (P = .01) of the R-R interval. The mean scores were 3.33 (± 0.96) for reconstructions from 50% and 3.32 (± 0.98) for reconstructions from 60% of the R-R interval.

For the descending aorta, the mean score for image quality was highest for reconstructions from 20% of the R-R interval (3.87 ± 0.57; P < .001). However, the overall image quality for evaluation of the descending aorta was considered diagnostic at all of the reconstruction time points tested (Fig 1).

The image quality for the pulmonary arteries (Figs 6, 7) was rated best when reconstructions were retrospectively referenced to 50%, 60%, or 80% of the R-R interval. For these time points, mean scores were 3.14 (± 0.90), 3.18 (± 0.86), and 3.50 (± 1.00), respectively. No statistically significant difference was found in image quality scores between these three time points; quality for these three time points together, however, was superior to the mean for the other three time points, 0%, 20%, and 40% (P = .01). For imaging of the left coronary artery and the left ventricular outflow tract, only two (7%) of 30 patients had image quality scores of less than 3.0 at the optimal R-R interval. Both patients were scanned for suspected pulmonary embolism, and both had comparatively high heart rates of 84 and 89 beats per minute.

### Discussion

Suitable parameters for retrospectively ECG-gated imaging of the coronary arteries with four-section multi-detector row CT technology have been described (11–13). There is slight variation in the exact time points of the R-R interval that were previously recommended as the starting point for image reconstruction, depending on the study and the coronary artery. However, there appears to be agreement in the literature that image reconstruction is preferably referenced to the diastolic phase of the heart cycle, when cardiac motion is at a minimum; image reconstruction during this interval is ordinarily used at CT angiography of the coronary arteries (4,18–20). The results of the current study reconfirm this intuitive concept also for the generation of 16-section multi-detector row CT scanners, which have higher temporal resolution.

In addition to enabling noninvasive visualization of the coronary arteries, ECG synchronization has been shown to improve CT image quality in other thoracic structures (7,8). In principle, retrospective ECG gating enables a reduction of
Radiology

Volume 233 · Number 3 · Cardiac Motion Suppression at ECG-gated 16-Section CT · 931

transmitted cardiac pulsation in more extensive scanning volumes. However, the through-plane spatial resolution along the patient axis that could be achieved with the retrospectively ECG-gated technique by using the previous generation of four-section multi–detector row CT scanners (ie, 2.5-mm section thickness) was limited by the relatively long duration of scanning, which exceeded the breath-holding capabilities of most patients. A long duration of scanning is necessary for oversampling of data with a slow CT scanner table feed to obtain sufficient image data for each x-, y-, and z-axis position within the scanning volume at each time point during the cardiac cycle. Acquisition of CT image data and of digital ECG tracings in this fashion is the basis for performing ECG-gated image reconstruction (10,15) retrospectively at any desired phase within the cardiac cycle. Thus, high through-plane resolution (ie, 1.00–1.25-mm section thickness) could be achieved only for relatively small volumes such as the coronary arterial tree, and not for extended coverage of the entire chest.

These limitations of the previous generation of four-section multi–detector row CT scanners may have precluded the more general application of ECG-synchronized acquisition techniques for vascular imaging in the chest. For imaging of the pulmonary circulation, for instance, the superiority of thin sections (ie, 1.00–1.25 mm) over thicker sections has clearly been demonstrated (21,22). If one had to choose between acquiring data with high resolution (ie, 1.00–1.25-mm section thickness) but without ECG gating or with lower resolution (ie, 2.50-mm section thickness) and with ECG gating, greater diagnostic benefit could ordinarily be gained with high-resolution protocols. High spatial resolution along the patient axis generally enables better assessment of minute pathologic entities such as isolated peripheral pulmonary emboli (22). In addition, the increasing clinical importance of three-dimensional display techniques for diagnostic-quality visualization of thoracic vascular anatomy (23) has fostered the concept of volume data acquisition with isotropic resolution (ie, voxels with equal dimensions in x-, y-, and z-axis directions), which could not be provided for larger scanned volumes when retrospective ECG gating with four-section multi–detector row CT was used. The advent of 16-, 32-, 40-, and 64-section multi–detector row CT scanners effectively has eliminated these limitations of the previous generation of scanners and enables scanning of the entire thorax with retrospective ECG gating and submillimeter through-plane resolution in a single breath hold.

While the benefit of retrospective ECG gating has been recognized—for example, in studies of ECG-synchronized CT angiography of the thoracic aorta (5,6,9,14,24)—systematic studies aimed at determining the optimal reconstruction time points for imaging of vascular structures other than the coronary arteries have been reported only for the thoracic aorta (6). As pulsation from the beating heart travels through the thorax, it cannot a priori be assumed that the same reconstruction intervals that are optimal for imaging of the coronary arteries can be applied with equal success to anatomic structures outside the heart. In our study, we demonstrated that, in a majority of patients, some phases of the cardiac cycle are substantially better than others for suppression of cardiac motion artifacts with retrospective ECG gating for 16-section multi–detector row CT angiography of thoracic vessels. Therefore, the results of our analyses performed in a representative sample of 30 consecutive patients with a wide range of heart rates may serve as general guidelines for the choice of reconstruction time points to suppress cardiac motion at multi–detector row CT of different vascular structures in the thorax, if such imaging is desired and clinically indicated. For any given individual, the most suitable image reconstruction interval for visualization of a particular thoracic structure may deviate from our cumulative findings in multiple patients. In such cases, use of a preview image series, a feature available at many workstations, enables reconstruction of data from different time points during the cardiac cycle at a single arbitrary level (eg, the origin of the left main coronary artery) so that the most suitable reconstruction interval for any given structure can be identified.

Apart from the benefit for dedicated imaging of the coronary arteries, the greatest benefit we experienced in using the ECG-synchronized scanning technique was artifact-free imaging of the aortic root and the ascending aorta, especially the elimination of potential sources of diagnostic error in assessment for type A dissection (1). Consequently, retrospective ECG gating has remained part of our routine protocol for imaging of the ascending aorta. Our findings for the thoracic aorta are also in good accordance with previously published results (6). Despite slightly better image quality with reconstruction of data acquired during complete cardiac contraction, at 20% of the R-R interval, in our sample the descending thoracic aorta was consistently well visualized at all reconstruction time points, and ECG-gated acquisition did not appear to add much diagnostic benefit for dedicated imaging of this structure.

The pulmonary arteries were optimally displayed somewhat later in the cardiac
cycle, during late diastole, a fact that may be explained by a certain delay in the pulsation wave as it travels through the thorax before reaching the pulmonary vessels. While the display of the pulmonary arteries can be improved with ECG gating, the effect of ECG synchronization appears to be somewhat less dramatic with a larger temporal window during which diagnostic image quality can be achieved compared with the fast-moving cardiac anatomy. We therefore recommend that ECG-gated acquisition of the pulmonary vessels be reserved for special indications: for example, to exclude isolated pulmonary embolism in paracardiac pulmonary arteries in cases in which an important treatment decision hinges on an unequivocal diagnosis as to the presence or absence of pulmonary emboli in these vessels.

Our study had a number of limitations. First, the study population was an inhomogeneous random sample of patients undergoing CT angiography of the thorax for a variety of clinical indications. This group of patients, however, should...
provide a more accurate reflection of the clinical reality than if patients had been selected according to predetermined characteristics (eg, heart rate or heart rhythm).

Second, the technique we tested has intrinsic limitations. Lack of doubt to recommend the general use of retrospective ECG gating for all contrast-enhanced vascular CT examinations in the thorax is mainly based on concerns related to patient radiation exposure, which is about three times higher for retrospectively ECG-gated protocols than for non-ECG-gated protocols (ie, 9–10 mSv vs 3–4 mSv). Radiation exposure is of special concern in younger patients undergoing repeat scanning. In addition, the relatively slow acquisition mode required for data oversampling for retrospective ECG gating results in relatively long breath-hold times for the patient, although in our patient cohort no gross respiratory motion artifacts were observed. Potential solutions to these limitations may consist in the more widespread implementation of methods aimed at reducing radiation exposure by using ECG-dependent tube current modulation (25). Shorter acquisition times with future generations of multi–detector row CT scanners that incorporate either additional detector rows or novel concepts of detector configuration may further enhance the usability of ECG-gated protocols.

A last limitation relates to our statistical analysis. Although sample normality may be verified by a goodness-of-fit test, the test was difficult to apply to all sample data included in this study for such verification.

We currently recommend the use of retrospective ECG gating for imaging of the heart, the aortic root, and the ascending aorta, especially when motion artifacts may critically influence the diagnosis (eg, cases in which aortic dissection is suspected). For imaging of other vascular structures in the thorax, ECG gating should probably be reserved for special cases in which reduction of cardiac motion artifacts is likely to result in a more accurate diagnosis. In such situations, the results of our current analysis may serve as useful guidelines for the selection of suitable image reconstruction intervals at retrospectively ECG-gated high-resolution 16-section multi–detector row CT of the thorax.

References