Importance of Viewing ECG Multiphase Data in the Clinical Interpretation of Coronary Angiography Using Multi-Detector CT Scanners

John A. Rumberger, PhD, MD, FACC
Professor of Medicine (Clinical),
The Ohio State University
Medical Director, HealthWise Wellness
Diagnostic Center, Dublin, Ohio

David Fein, MD
Medical Director, The Princeton
Longevity Center
Princeton, New Jersey

Corresponding author:

John A. Rumberger, PhD, MD, FACC
HealthWise Wellness Diagnostic Center
5747 Perimeter Drive, Suite 105
Dublin, Ohio 43017
Phone: (614) 652-5888
Email: jrumberger@healthwisecenter.com

Introduction

The recent introduction of 64-slice multi-detector CT (MDCT) has issued in a new age for accurate, non-invasive detection of segmental coronary atheromatous plaque and stenoses [1]. It has also made practical applications for dynamic cine-angiographic imaging of the left ventricle, initially validated for electron beam cardiac CT over 20 years ago [2, 3].

The excellent sub-millimeter spatial resolution of 64-slice MDCT now affords the ability to produce cubic or nearly cubic ('isotropic') volume-elements (voxels) during CT image reconstruction. Three-dimensional image rendering using sophisticated 3D computer workstations then provides high fidelity images in an infinite number of spatial planes. MDCT with 64-slices also has faster rotational speeds (in the range of 330-400 msec) than its 8- and 16-slice predecessors did. Spatial symmetry then affords a nominal temporal resolution (at 180 deg of arc) of 160-200 msec. However, these speeds still represent fully 20% or more of the cardiac cycle at a normal resting heart rate of 72 beats/minute. Such rates are thus insufficient by themselves to capture motionless coronary images without retrospective gating and compilation of phase imaging derived from multiple cardiac cycles. Although CT manufacturers have introduced two and up to four 'partial scan' reconstruction methods for high resting heart rates to improve the apparent temporal resolution, these can still fail at specific 'harmonic' heart rates depending on individual design. The use of beta-blockade to reduce cardiac motion further during specific cardiac phases remains commonly applied when heart rates are nominally above 65 beats per minute. Motion artifacts are then common in 64-slice MDCT coronary images, leading to misregistration of the coronary arteries and the potential for misdiagnosis.

The following will discuss aspects of using 64-slice MDCT reviewing multiple reconstructed ECG RR-interval phase images to facilitate accurate, non-invasive definition of coronary artery plaque and stenoses. In order to accomplish the interpretation task in a rapid and convenient manner, it is also essential that the workstation employed be able to load multiple phases as a single large dataset.

Cardiac/Coronary Motion during the Cardiac Cycle

Throughout the cardiac cycle, the heart changes in spatial location and conformation and individual coronary ballistics are complex and three-dimensional. The acronym **TARTTS** can be applied for characterization of cardiac motion during each heartbeat. As such, the heart **T**ranslates [physically moves across the tomographic plane], **A**ccordions [with a piston-like motion involving descent of the base of the heart and ascent of the apex], **R**otates [about an ill-defined vertical (or long) axis, which is likely curved and not linear], **T**ilts [about another axis which wobbles again about the ill-defined vertical axis, sort of like the Earth tilting with the change of seasons], **T**hickens [with increase in left ventricular wall thicknesses, but with no net change in muscle mass or total intra-pericardial volume], and finally, **S**queezes with a wringing motion. These motions are interdependent. The base of the heart descends about 1 cm and the apex ascends about 1 cm with each cardiac cycle. The major epicardial arteries are from 3-4 mm in diameter at the left main to about 1 mm at the distal LAD (left anterior descending) coronary artery. Studies have shown that the LAD moves during each cardiac cycle at a rate of 22 mm/sec on average, and that the velocity can be more than 3-4 times that value for portions of the right coronary artery (RCA) [4]. Furthermore, the total excursion of the artery during the cardiac cycle is a distance that can be multiples of its own diameter. This motion can be illustrated in a single tomographic plane, as shown in Figure 1.

Cardiac motion accelerates during early systole, rapidly decelerates at the end of systole, accelerates a bit more slowly (and in the opposite direction) during early diastole, and then accelerates a bit more slowly to return to its original position during late diastole. Generally, the slowest rates of acceleration/deceleration of cardiac motion occur at or near end-systole and in the mid- to later phases of diastole. Figure 2 shows a coronary 'ballistocardiogram' representing changes in velocity of the right coronary artery during the ECG-RR cycle. Tomographic imaging creates another issue, as the plane in which the artery is imaged at end-diastole is not the same physical (or anatomic) plane containing the same arterial segment at end-systole.

Even at rapid scan rates of less than 100 msec for electron beam CT, image phase can have significant effects on quantitative coronary calcium scoring

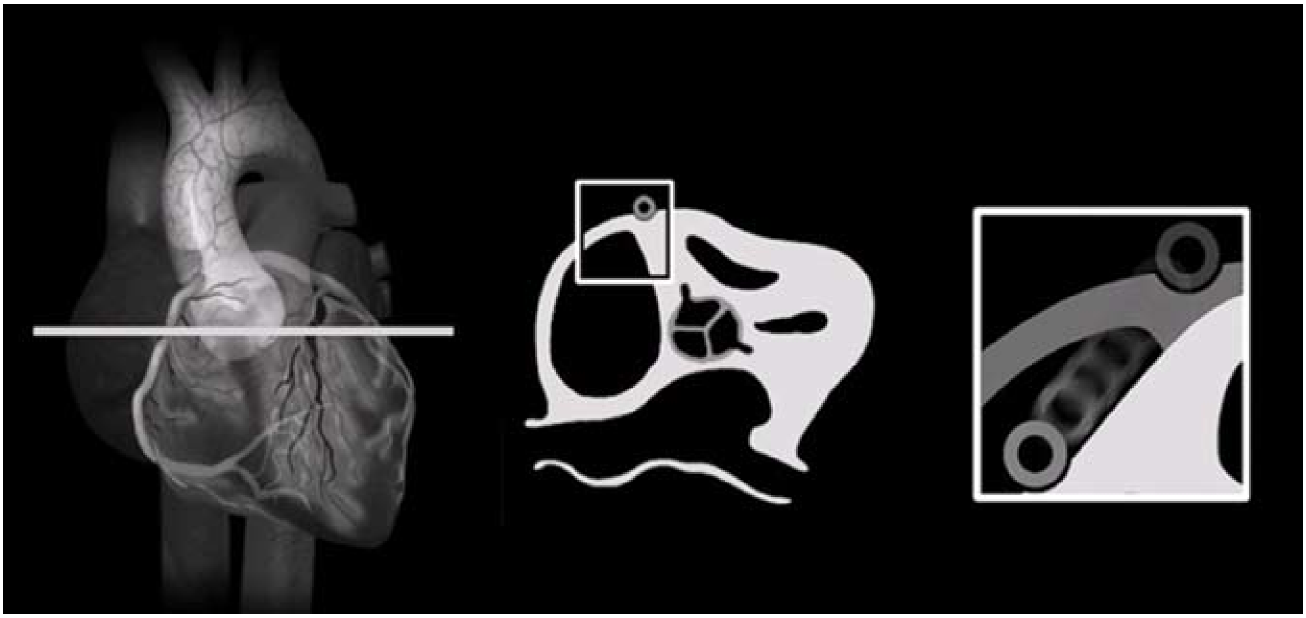


Figure 1: A schematic of coronary motion during the cardiac cycle. Note that the artery can move within the tomographic plane several vessel diameters with each heart beat.

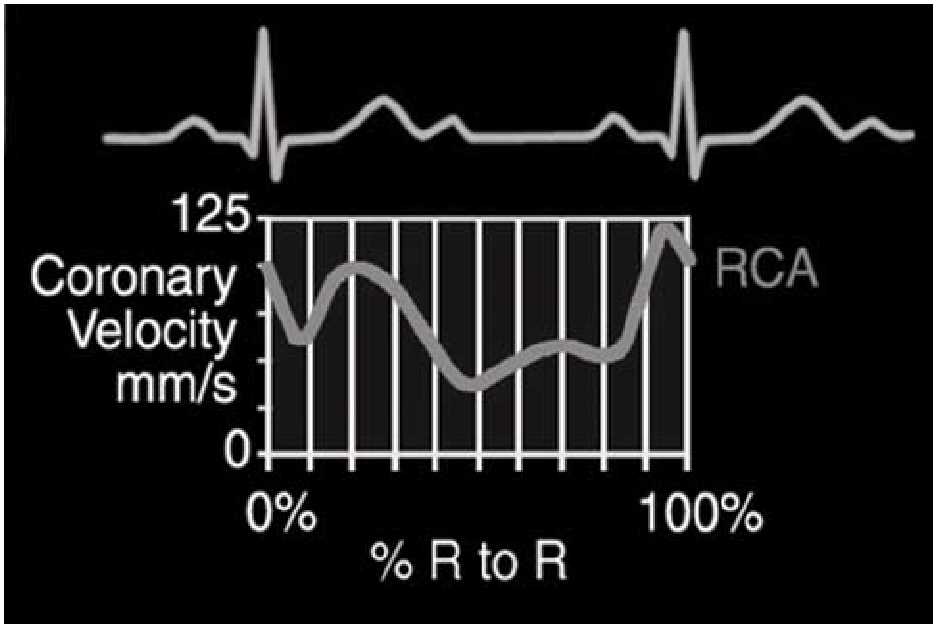


Figure 2: Coronary artery velocities during the cardiac cycle. For illustrative purposes, the cardiac ECG RR-intervals are divided into ten phases. RCA = right coronary artery. mm/s = millimeters/second

(Figure 3). These effects can be even more devastating if attempting to quantify common features on CTA such as 'soft' (non-calcified) plaque. The least motion during phase reconstruction is achieved when the actual displacement of the coronary artery in question is least, usually at or near end-systole and during the early and later phases of diastole. Image reconstruction for 64-slice MDCT can be calculated at any chosen ECG-RR interval (phase). However, as the number of reconstructions increases, interpretation time increases accordingly, requiring a powerful workstation that can shift through these huge data sets in a rapid, consistent and convenient manner.

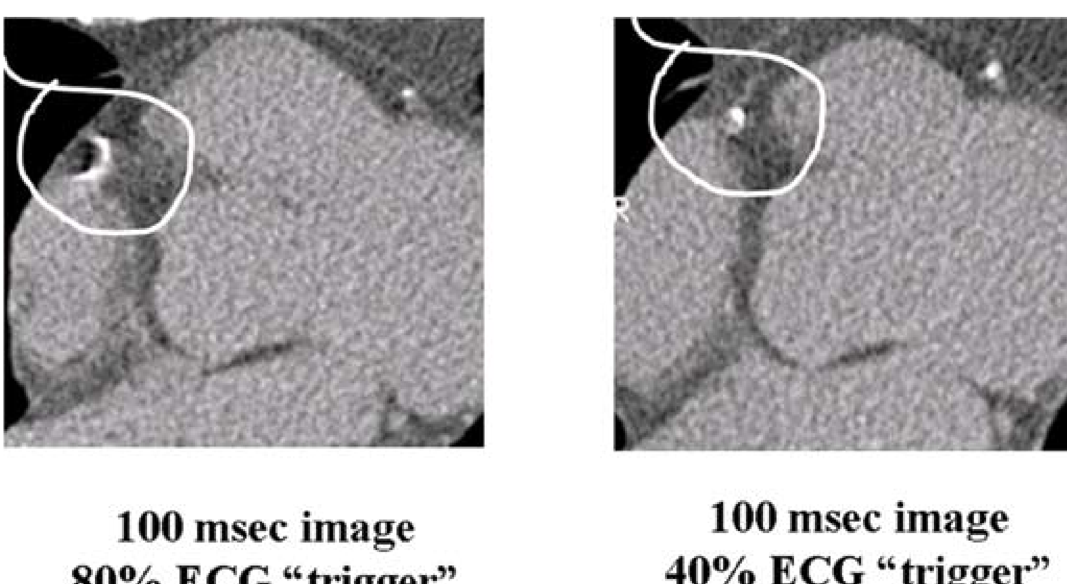


Figure 3: Example of motion artifacts in the RCA at different cardiac phases for coronary calcium scoring. See text for discussion.

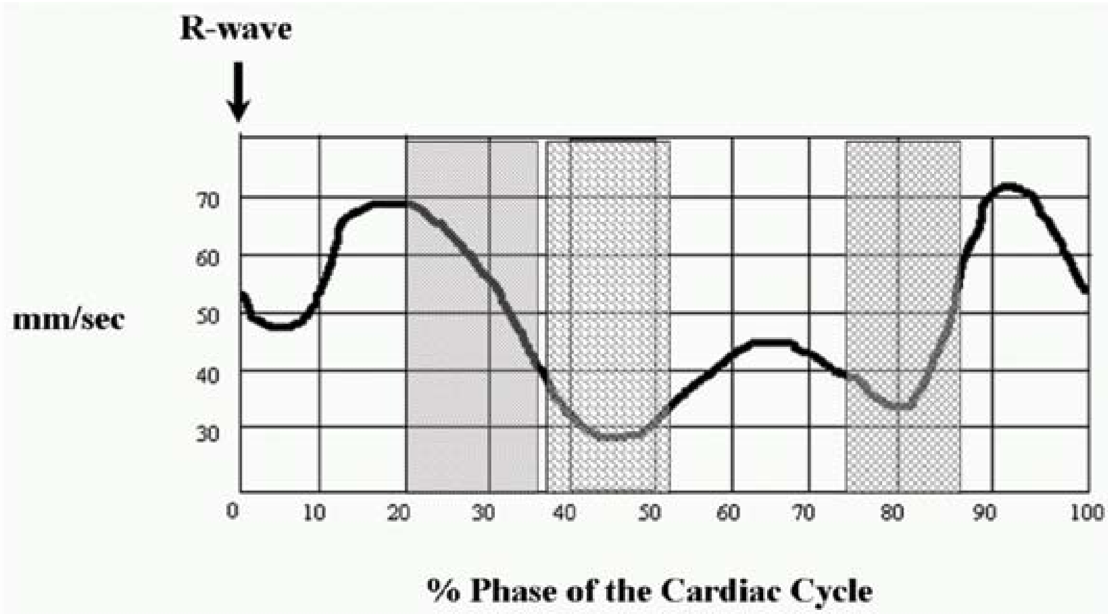


Figure 4: Examples of phase reconstruction intervals for 64-slice MDCT during the cardiac cycle. See text for details.

Determining the optimum segment of the heart cycle for CT image reconstruction is complicated also by the fact that the relationship between cardiac phase and the ECG R-wave varies nonlinearly with heart rate. Additionally, at a slow heart rate, systole occupies roughly 1/3 of the cycle and diastole 2/3; as heart rate increases, systole increases and diastole decreases to roughly 50% each of the heart cycle. Thus, the reconstruction phase (either as a percentage of the RR-interval or at a fixed time-delay after the R-wave) that is optimal at one heart rate may contain motion artifacts at a different heart rate, even in the same patient.

Figure 4 provides an example of potential phases pre-defined for image reconstruction. The velocity and displacement of the RCA is greater at or during the 30% RR phase interval reconstruction than might be seen for images reconstructed at the 45% (end-systole), 65% (early diastole), and 85% (late diastole) phases.

Clinical Examples and Issues of Multiphase Imaging Using MDCT

Motion of the coronary artery should be minimal during the reconstruction phase to avoid errors in image interpretation. Stenoses may be misinterpreted in MIP/MPR (maximum intensity projection/multiplanar reformations) as well as VRT (volume rendered) images if motion artifacts are introduced.

Entire coronary arteries can be missing from images reconstructed at certain ECG-RR phases. Figure 5 shows a VRT reconstruction of the LAD. Note that the first diagonal artery (top arrows) is not visible and features of the more distal LAD are 'smoothed' (bottom arrows) when comparing the 30% with the 75% RR phase image.

Torsion of the heart during the cardiac cycle may induce different levels of motion in various portions of the same artery system. For instance, the twisting or wringing motion may move the proximal vessel in one direction at a time when the distal portion is moving in a completely different direction, as illustrated in Figures 6-8.

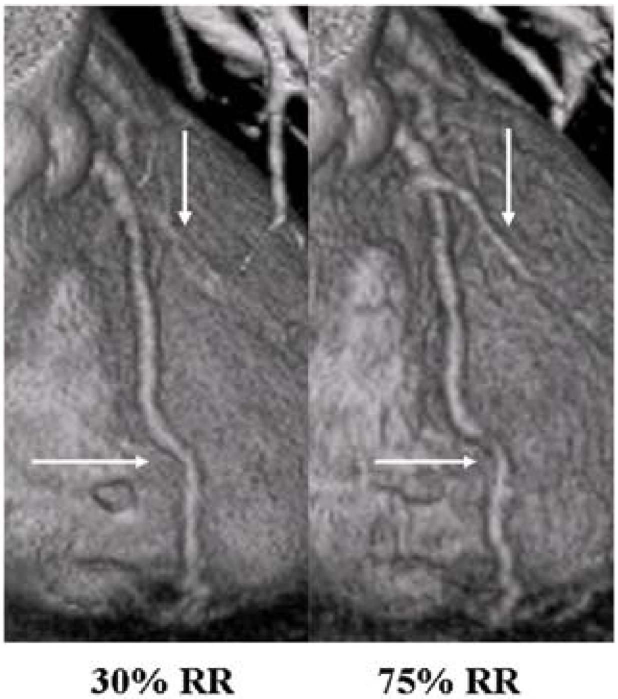


Figure 5: Example of VRT image of LAD at 30% RR phase and 75% RR phase. See text for details.

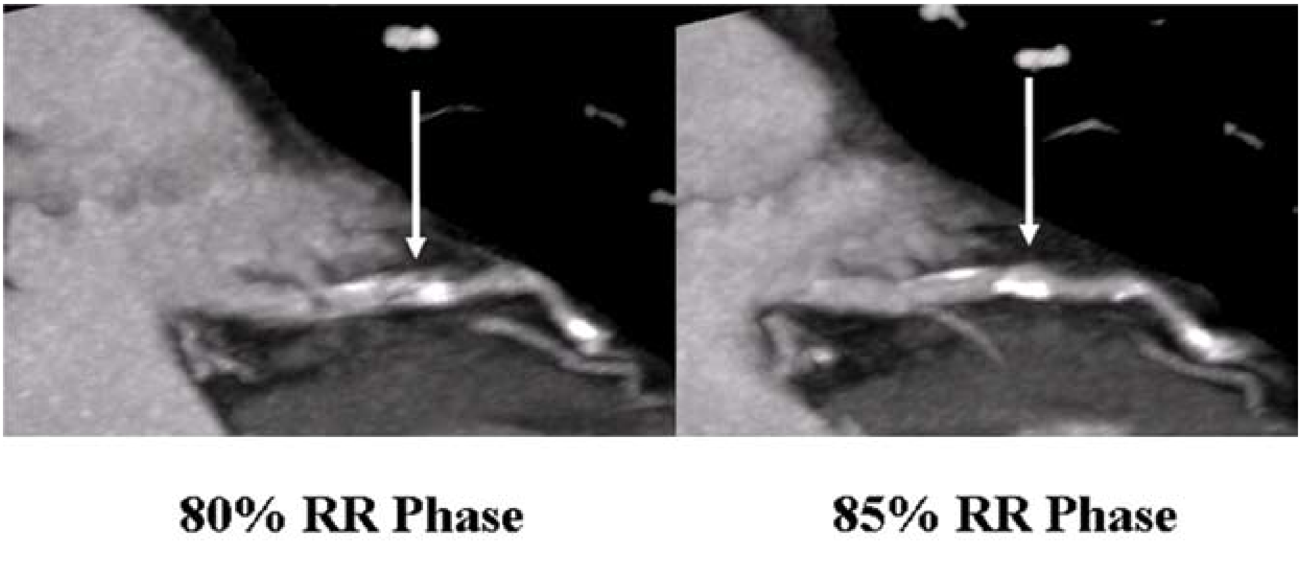
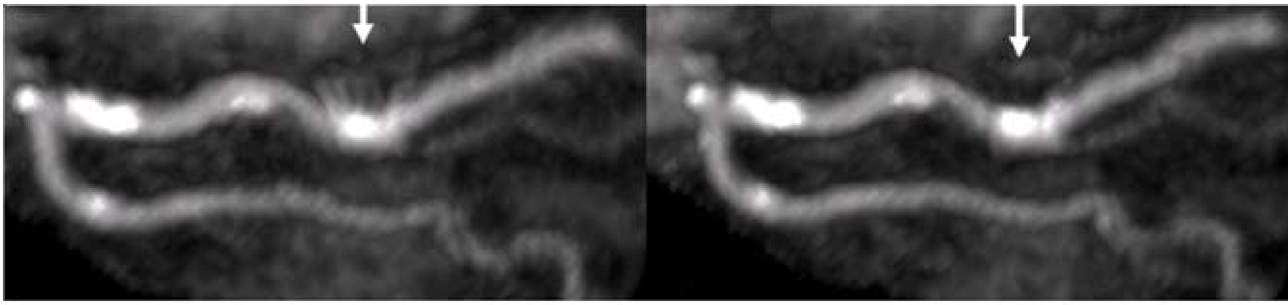
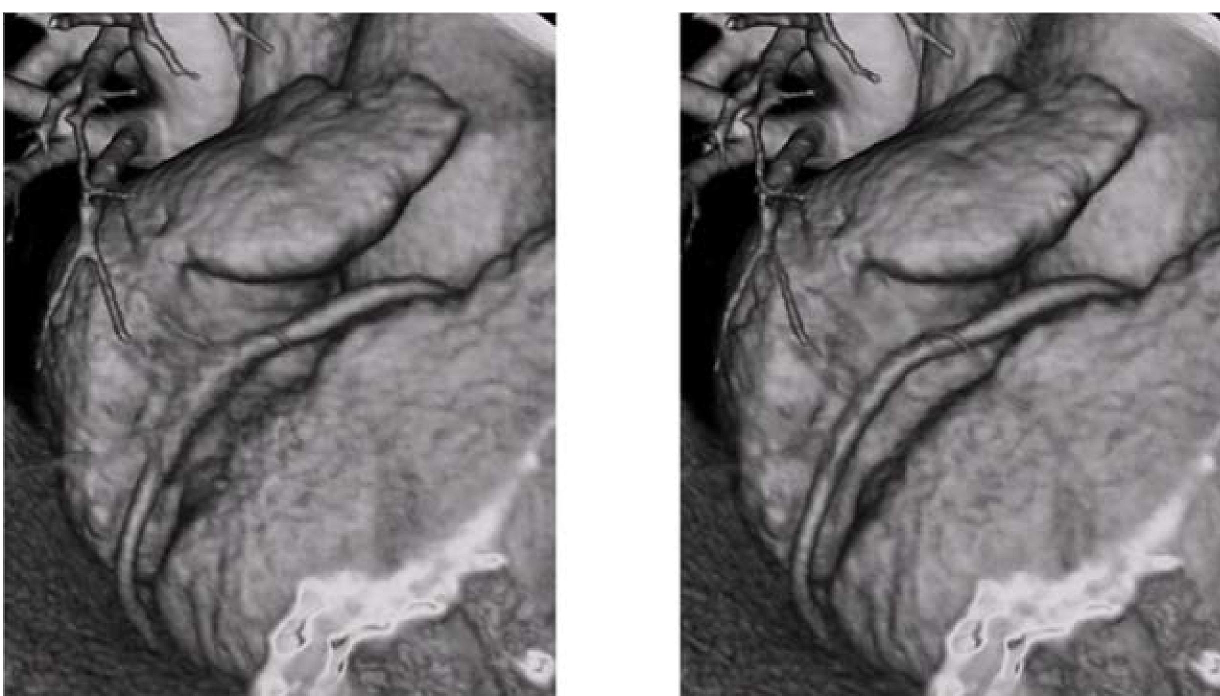


Figure 6: Motion in proximal LAD. Even small variations in RR phase, here between an 80% and 85% RR phase, can distort the coronary fidelity, especially complicating interpretation when complex (hard and soft) plaque are present.



75% RR Phase **85% RR Phase**

Figure 7: Motion artifacts can distort specific segments of the coronary artery, even while the remainder of the artery is motion free.



70% RR **85% RR**

Figure 8: VRT images show isolated motion artifacts in the mid RCA apparent on the 70% RR phase reconstruction but not on the 85% RR phase reconstruction.

Discussion and Recommendations

What is the best approach? Generally, a ten-phase study can accurately define global and regional left ventricular function. As shown in Figure 4, the phases in which coronary artery motion is minimized are near end-systole (roughly at 45%), again in early diastole (roughly 65%), and/or in late diastole (roughly 85%). Conversely, a poor initial reconstruction interval for coronary analysis would be at 30% of the RR interval.

Some CT scanner manufacturers assign the starting RR phase for reconstruction, while others reconstruct from the center point. The optimum phase for minimizing motion may therefore appear to vary from scanner to scanner depending on how phases are calculated and labeled. This is most likely to be of concern for a physician interpreting CTA from several scanner platforms. In particular, Toshiba, Phillips, and General Electric use the center point RR phase, while Siemens specifies the start phase of the reconstruction. For illustrative purposes, consider a scanner temporal resolution of 200 msec and a heart rate of 60 beats per minute (RR-interval of 1,000 msec). A chosen phase of 50% would result in reconstruction from 400 to 600 msec after the R-wave with the center point definition, but from 500 to 700 msec by the start point definition. Thus, one must be aware that the defined 'best phase' for motion-free imaging depends on the CT scanner even in the same patient and same heart.

Given the above stipulations, review of images from mid- to late-diastole reconstructed at 65%, 75%, and 85% RR phase are acceptable for most coronary segments when the heart rate is <65 beats per minute. When the heart rate is faster, it often becomes necessary to reconstruct images from end-systole as well. As a rule, we recommend reconstruction of at least three phases, such as at 45%, 65-70% and 75-80% RR phase. Further phases can be reconstructed from the raw data set if needed, but this can result in interpretive delay. A process similar to 'bracketing' in photography can be used, wherein the same photograph is taken at the desired exposure and one f-stop above and below, in order to maximize chances of acquiring an optimal image. For example, if one finds that the 75% RR phase produces the best motion free images, then adding reconstructions at 70% and 80% would be prudent. At faster heart rates, setting up additional phases at 40%, 45%, and 50% at the time the study is being performed will most likely save interpretation time in the end.

When calcified plaque is present, choosing the phase with the sharpest edge to the calcification may avoid over-estimating the degree of stenosis. When non-calcified plaque appears to be present, viewing multiple phases of that location may reveal that an apparently significant stenosis at one phase can be substantially less significant or even disappear at another phase. Care must also be taken to ensure that motion-induced blurring has not rendered a significant stenosis invisible. Choosing the phase with the sharpest arterial edge can help avoid this error. Nevertheless, viewing reconstructions at several phases provides the highest confidence in interpretation and should be performed routinely in all studies.

As noted in the introduction, in order to facilitate rapid and convenient 64-slice (or greater) MDCT coronary angiography analysis, it is essential to be able to review these large datasets as a whole. In this aspect, all modern day workstations are not created equal. Many workstations that can accomplish MDCT angiography review are unable to load all phases of the coronary angiography study into active memory. The TeraRecon Aquarius® Workstation employs both a software solution (as is employed by other workstations) AND a unique 'hardware solution', the Volume-Pro board, to manage these large data sets (consisting of 3,000 to 4,500 images at present). It is essential for accurate diagnosis that a workstation support fast loading of all the ECG-phases as well as interactive switching between them during diagnostic review. The Aquarius® Workstation offers the ability to seamlessly (and in a straightforward manner) 'page' though the phases at any given anatomic site to arrive at the one which represents the least or absent motion artifact. This 'phase' may be different for certain vessels or even within a given vessel (as noted above). In addition, the Aquarius® informs the reader of the RR phase that is currently being evaluated.

In our experience, the failure to appreciate subtle motion artifacts and their potential to mislead interpretation during diagnostic review can compromise the clinical utility of any 64-slice study to quantify coronary atheromatous plaque, even if the examination was properly performed technically.

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