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CORONARY ARTERY IMAGING

Three-Dimensional, Time-Resolved Motion of the Coronary Arteries

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ABSTRACT

Background. Coronary artery motion can decrease image quality during coronary magnetic resonance angiography and computed tomography coronary angiography. *Purpose.* To characterize the three-dimensional motion of the coronary arteries along the entire vessel length and to identify the temporal location and duration of periods of relatively low cardiac motion in patients with coronary artery disease. *Methods.* Archived digital, biplane x-ray angiography films acquired at 30 frames per second with simultaneous electrocardiogram recording were reviewed for 15 patients with coronary artery disease. The right coronary (RCA), left anterior descending (LAD), and left circumflex (LCX) arteries were divided into proximal, mid, and distal segments. The displacement and velocity of a point in each segment were calculated throughout the heart cycle. Time-dependent, three-dimensional motion of each segment on each vessel was determined. Periods of the heart cycle during which maximal displacement was less than 1 mm or 0.5 mm per frame for each artery were determined. *Results.* A period lasting an average of 187 msec was seen during mid-diastole (72±5% of the cardiac cycle) in which all three coronary arteries studied had relatively little motion. This period of quiescence was consistent along the length of the arteries. Although the amount of motion did vary along the length of the arteries, there was no difference in the timing of rest periods in the proximal, mid, and distal segments using a <1 mm per frame threshold. The periods of low motion were

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significantly reduced in length and often altogether eliminated when the 0.5 mm per frame threshold was used.

Key Words: Coronary artery motion; Coronary artery disease; CT; MRI; Coronary angiography.

INTRODUCTION

The current gold standard for visualization of the coronary arteries and diagnosis of coronary artery disease is catheterization and x-ray angiography. This procedure requires local anesthesia, catheterization of the femoral artery, iodinated contrast agent, and ionizing radiation exposure to obtain the diagnostic images. Although catheterization and x-ray coronary angiography are now commonplace in many facilities, there still are nontrivial risks of kidney damage, damage to blood vessel linings, and even mortality (Grossman, 1986). These risks prevent x-ray angiography from being used as a screening tool. To address the need of noninvasive imaging of the coronary arteries, magnetic resonance angiography (MRA) and computed tomography (CT) coronary angiography have been developed.

Magnetic resonance angiography has great promise as a screening and diagnostic tool for coronary artery disease. It has excellent soft tissue contrast that allows for visualization of surrounding cardiac structures; MRA is noninvasive, uses no ionizing radiation, and does not require hospitalization. Advances in MRA have led to its widespread use in cerebrovascular and renovascular screening (Borrello, 1997; Derdeyn, 2001; Norton, 2003; Olin, 2002; Perez-Arjona et al., 2002; Prince, 1998). However, due to technical limitations, the use of MRA for detection of coronary artery disease has had limited utility. The major technical limitation is that the image quality of MRA for the coronary arteries is vulnerable to motion artifacts caused by cardiac and respiratory motion. Respiratory motion can be minimized by use of either breath-hold techniques or navigator-gated techniques (Edelman et al., 1991; Huber et al., 2001; Manning and Boyle, 1993; Oshinski et al., 1996, 1998; van Geuns et al., 1999). However, motion of the heart during the cardiac cycle must be attenuated with additional methods. Most commonly, coronary MRA is performed during periods of the cardiac cycle when coronary motion is least to minimize the blurring effects of motion. Typically, a transverse cine of the heart is obtained to view a middle segment of the right coronary artery (RCA) in cross section. The frame-to-frame motion of the mid-RCA is followed, and the phases with the least displacement between them are then chosen as the timing window during subsequent coronary MRA (Wang et al., 2001). However, this technique only evaluates in-plane motion of the middle segment of the RCA and assumes through-plane motion is not significantly different. Furthermore, this method assumes that segments of all three coronaries have similar motion properties.

New spiral CT techniques with electrocardiogram (ECG) gating are also being developed to visualize the coronary arteries (Knez et al., 2000). With retrospective ECG gating, data acquisition that occurred only during a defined time window at certain points of the cardiac cycle is used to reconstruct images. To shorten the acquisition window, thereby decreasing blurring from motion artifact, data from two or more consecutive cycles can be reconstructed to form a single image (Kachelrieb et al., 2000; Klingenbeck-Regn et al., 2002; Kopp et al., 2001). Several studies using ECG-gated spiral CT coronary angiography have demonstrated improvements in image quality with reduced motion artifacts; but blurring is still evident in patients with higher heart rates (Achenbach et al., 2000a; Giesler et al., 2002; Jakobs et al., 2002; Kachelrieb et al., 2000; Nieman et al., 2002; Ropers et al., 2003).

For coronary MRA and CT coronary angiography to reach their full diagnostic potential, artifacts due to cardiac motion must be further reduced. Specifically, the duration and location of relative quiescence of the coronary arteries need to be determined. This information could be used to prospectively determine the optimal image acquisition window for coronary MRA and to retrospectively select the reconstruction window for CT coronary angiography. Previous research has used biplane x-ray angiography films to track the motion of the RCA and left coronary arteries (Wang et al., 1999). Wang and coauthors identified rest periods of 161 msec and 120 msec (averages for left anterior descending and right coronary artery, respectively) but did not locate those periods within the cardiac cycle and did not characterize the entire three-dimensional (3D) motion at different points along the vessels. Other studies have examined the motion of the coronary arteries in two dimensions but did not analyze through-plane motion (Lu et al., 2001). The purpose of this study was to: 1) quantitatively describe the complete three-dimensional pattern of coronary tree motion, 2) examine differences in motion along the length of the coronary vessels, and 3) characterize the temporal location and duration of periods of low motion in coronary vessels. Biplanar x-ray angiography, coupled with ECG-gating data, was used as the basis for the analysis.

METHODS

Patients

This study was approved by the institution review board of Emory University and the Atlanta VA Medical Center. We reviewed digitally archived, ECG-gated,

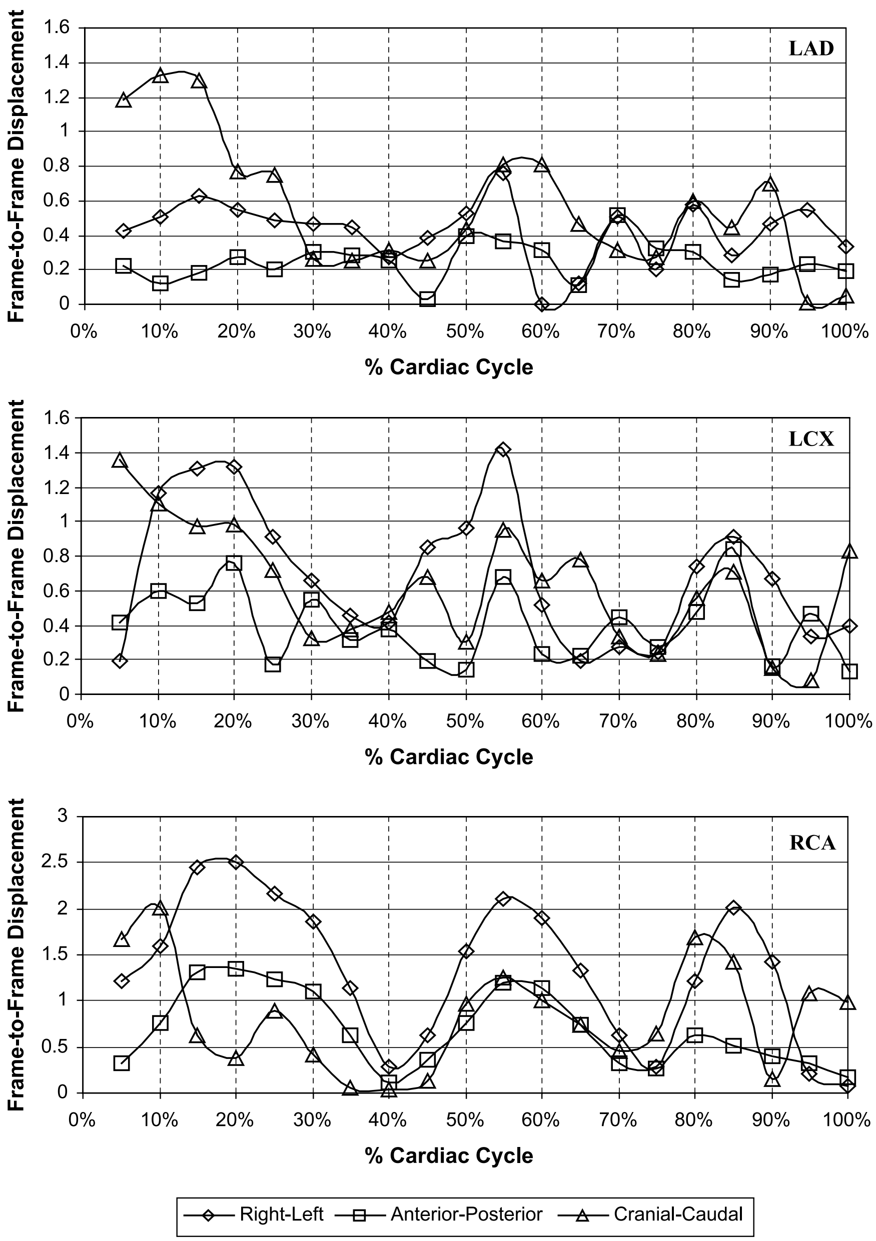

Figure 1. Displacement of the middle segment of the three coronary arteries along orthogonal axes. Motion of the LAD and LCX is predominantly in the cranial-caudal direction while motion of the RCA is predominantly in the right-left direction. Periods of low motion are seen at approximately the same times in the cardiac cycle in each direction. Note that RCA motion is on a greater scale than LAD and LCX motion.

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biplane angiography films of 15 patients with coronary artery disease. The patients were all males with average age of 55 years (range 45–68 years). The average heart rate of patients reviewed for this study was 66 beats per minute (range 49–82). All patients had also been diagnosed with either hyperlipidemia or hypercholesterolemia. Seven patients had hypertension and four patients were smokers. Each patient had undergone routine diagnostic cardiac catheterization with biplane cine angiography and simultaneous ECG recording. Angiography was performed during breath hold to minimize the effects of respiratory motion. Digital images were recorded at 30 frames per second and stored on optical disk for future review.

Image Review

Archived catheterization films were selected on the basis of the following criteria: 1) film has a distinct and periodic ECG readout without arrhythmia for at least two beats during contrast infusion; 2) film has a stationary point of reference (usually the catheter tip) for at least one heart beat (no panning); 3) film has clear resolution of the coronary artery in question including visible landmarks in the proximal, mid, and distal vessel in both views; and 4) patient has normal coronary artery anatomy (no anomalous coronary vessels).

In each catheterization film, the right coronary artery (RCA), left anterior descending (LAD), and left circumflex coronary artery (LCX) were reviewed. In most cases, only one artery was studied per film. In four patients, however, both the LAD and LCX met the inclusion criteria and could be clearly seen in the same film. Two orthogonal views were studied for each coronary artery to evaluate displacement in three dimensions. Landmarks on the proximal, middle, and distal points of all three coronary arteries that could be seen on both orthogonal views were identified, and their positions were tracked over the cardiac cycle. The landmarks were generally the takeoff of small vessel branches. Overall displacement between successive frames was determined for each landmark over the cardiac cycle. To isolate coronary motion from any respiratory motion, movement of the reference point (catheter tip) was also tracked in each frame of the cine and subtracted from the observed motion of coronary landmarks. Frame-to-frame displacement was measured in three perpendicular directions (two on one angiographic view and one on the other orthogonal view); hence, 3D motion was evaluated. Measurements were made by manually placing a cursor over each landmark and recording the spatial coordinates (in pixels) of the point in two planes using medical imaging software (OSIRIS Medical Imaging software, University Hospital of Geneva, Switzerland).

Image Data Analysis

Data were analyzed in two ways: 1) the 3D motion of each segment of each vessel was determined and 2), the temporal position and duration of low motion within the cardiac cycle were determined.

For the 3D motion analysis, spatial coordinates of the landmarks were transformed to take into account

Table 1. Minimum and maximum step displacements and total range of motion in 3D and orthogonal axes.

		3D motion			R–L	A–P	C–C
		Min step	Max step	Total	Max step/Total	Max step/Total	Max step/Total
LAD	Prox	0.36	1.63	6.01	1.22/4.53	1.03/2.37	1.32/5.70
	Mid	0.39	1.46	6.07	0.63/3.81	0.31/1.82	1.32/5.65
	Distal	0.22	1.62	6.02	1.34/2.97	0.87/2.50	1.52/5.88
LCX	Prox	0.33	1.60	5.17	0.75/3.94	0.42/1.59	1.50/5.63
	Mid	0.44	1.83	8.31	1.32/6.78	0.76/3.29	1.35/6.28
	Distal	0.24	2.07	9.65	1.37/7.15	0.75/3.83	1.52/6.93
RCA	Prox	0.21	2.56	12.06	2.24/10.73	1.18/5.21	1.47/4.86
	Mid	0.31	2.88	16.08	2.51/13.28	1.35/6.83	2.01/8.33
	Distal	0.36	3.03	11.45	1.55/10.81	0.84/5.32	1.38/6.17

Abbreviations: LAD = left anterior descending; LCX = left circumflex; RCA = right coronary artery; Prox = proximal; R–L = right-left; A–P = anterior-posterior; C–C = cranial-caudal.
Step defined as interpolated 5% of the cardiac cycle. All displacement values are in millimeters.

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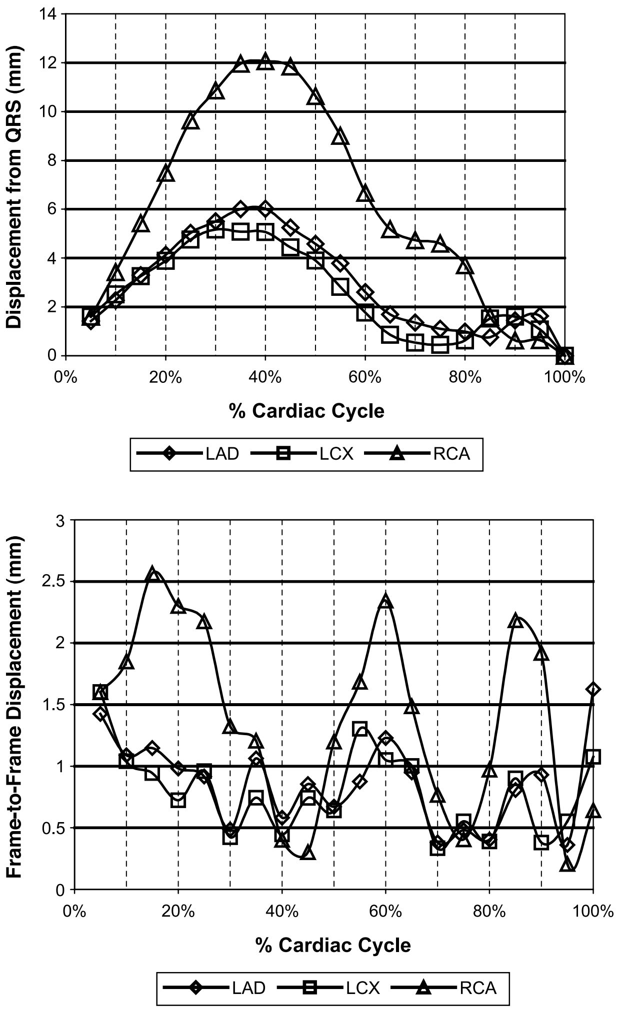

Figure 2. Motion of the coronary arteries averaged over all patients is plotted as net displacement from the QRS complex and as frame-to-frame displacement in 5% increments of the cardiac cycle. Displacement of the RCA is greater than twice the LAD and LCX displacement at most points of the cardiac cycle.

the capturing angles of the two cameras used to acquire the angiography images so position and displacement data for the three landmarks on each of the coronary arteries existed in a standard, orthogonal axis coordinate system relative to the human body (left-right, anterior-posterior, and cranial-caudal). To pool results from patients with different heart rates, the data were interpolated to yield displacement values of the proximal, middle, and distal landmarks at 5% intervals of the cardiac cycle. Cardiac cycle timing was defined as starting at one QRS complex (0%) and finishing at the next QRS complex (100%).

Following the work of Wang et al. (1999), a period of low motion was defined as any period in which the 3D displacement $[(\Delta x^2+\Delta y^2+\Delta z^2)^{1/2}]$ from one cine frame to the next was less than a set threshold value. We analyzed displacement at a threshold value of 1.0 mm, which corresponds to a speed of less than 30 mm/sec. We also analyzed displacement with a threshold value of 0.5 mm. The duration of low-motion periods for each artery and their location in the cardiac cycle were identified and recorded for comparison. Location and duration of the periods were defined from the original cine images acquired at 30 frames per second (no interpolation to 5% intervals was done). Curves of displacement vs. time in the cardiac cycle were created, and maximum and average displacements were determined for each vessel segment. Maximum (or total) displacement is defined as the largest net displacement seen from time zero, rather than integrated displacement or total distance traveled over the cardiac cycle.

RESULTS

3D Analysis of Motion

The motion of the LAD and LCX (averaged over the proximal, mid, and distal segments) was predominantly in the cranial-caudal (CC) plane compared to the right-left (RL) plane or the anterior-posterior (AP) plane. On average, more than half the motion of the LAD was in the CC plane (59±11%) with some movement in the RL plane (26±7%) and little motion (15±5%) in the AP plane. The LCX showed similar characteristics with predominant motion in the CC plane (48±10%) compared to the RL plane (33±7%) and the AP plane (19±5%). Most of the motion in the RCA, however, was observed to be in the RL plane (48±7%) with relative motion in the AP and CC planes of 22±5% and 31±9%, respectively. Although the magnitude of motion in each plane varied, the timing of rest periods was consistent in each direction (Fig. 1).

Vessel Displacement

The largest maximum total coronary displacement was 16.08 mm observed in the midsegment of the RCA (maximum mean displacement of the patients). Maximum displacement of the other arteries was 9.65 mm in the distal LCX and 6.07 mm in the mid LAD (Table 1).

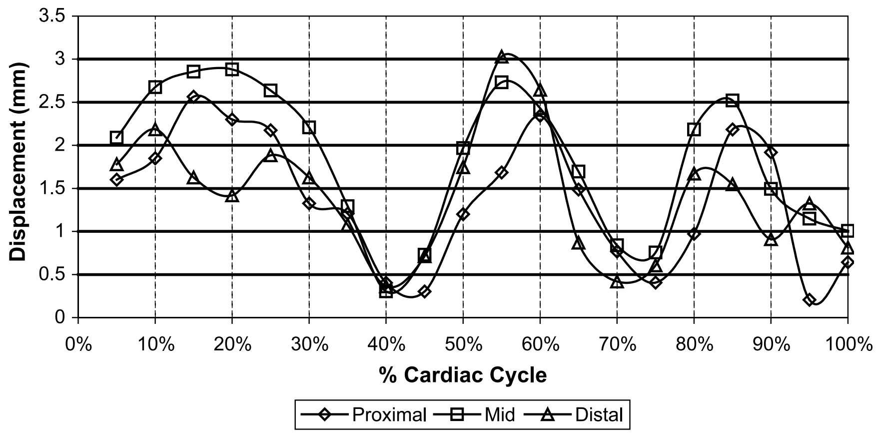

Figure 3. Displacement of the proximal, middle, and distal segments of the right coronary artery plotted over the cardiac cycle. Each segment experiences a similar motion trajectory, although the mid and distal segments have slightly more motion.

Maximum RCA displacement was up to 2.5 and 3.2 times greater than the LAD and LCX, respectively, and average RCA displacement was 2.1 and 2.2 times greater than the LAD and LCX displacement, respectively (Fig. 2).

Motion Along Vessel Length

Analysis of the individual segments (proximal, middle, and distal) of the RCA is shown in Fig. 3. The ratio (prox-mid-distal) of the displacement in RCA segments was 1:1.6:1.4 with a significant difference between the mid and proximal segments as well as between the mid and distal segments ($p<0.005$). Likewise, displacements in the mid and distal portions of the LCX were significantly greater than the proximal segment (ratio 1:1.5:1.6, $p<0.005$). The LAD, however, did not show any significant difference in magnitude of motion among its three segments (ratio 1:1.1:1.0). See Table 2. Despite the variation in magnitude of displacement along the length of the RCA and LCX, the temporal location of periods of low motion was similar in each of the three segments. The timing of low-motion periods was also consistent along the length of the LAD.

Periods of Low Motion

All three coronaries had two periods of relatively low motion, when frame-to-frame displacement was <1 mm. The first period occurred at 34±8% of the cardiac cycle after completion of ventricular systole. The average length of the first period was 118 msec (range 0–231 msec). The temporal location of the first rest period varied greatly among the different regions of the three coronary arteries (Fig. 4). In three subjects, there was no systolic period of low motion. The second period occurred at 72±5% of the cardiac cycle, after relaxation of the ventricles. This second period was generally longer than the first period, lasting an average of 187 msec (range 66–330 msec). The timing of the second period of low motion was less varied in the segments of the different arteries (Fig. 4). Frame-to-frame displacement increased again in late diastole during atrial systole. The length of each rest period was plotted against heart rate and an inverse relationship was noted: as the heart rate increased, the duration of rest shortened (Fig. 5).

Data were also analyzed for time periods during which frame-to-frame displacement was <0.5 mm. Under this restriction, the number of rest periods decreased by 64% and the average duration of the remaining rest periods also decreased 62 msec. Twenty-nine of 45 artery segments studied had no systolic rest

Table 2. Average ratios of motion in mid and distal segments of LAD, LCX, and RCA compared to the proximal segment.

	LAD	LCX	RCA
Mid	1.1	1.5*	1.6*
Distal	1.0	1.6*	1.4†

*$P<0.005$ compared to motion in proximal segment.
†$P<0.005$ compared to motion in midsegment.

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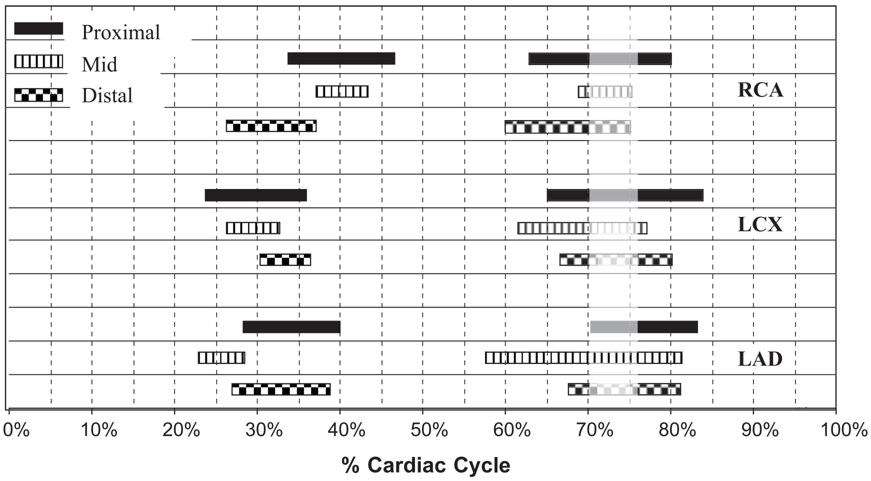

Figure 4. Average location and length of periods of low motion for the coronary arteries. The rest periods following ventricular systole are shorter than the rest periods in diastole and occur at different times of the cardiac cycle and no single time window covers all vessels. A window of the cardiac cycle exists from 71% to 76% (shown shaded in the figure) after ventricular relaxation during which all segments of the three coronary arteries had on average less than 1 mm frame-to-frame displacement in the angiography cine.

period. Nineteen of 45 artery segments studied had no rest period in the entire cardiac cycle.

It is also important to note that during no interval were any of the coronary arteries truly ‘‘motionless.’’ This unavoidable motion was, on average for the three arteries, 0.32 mm/step or 7 mm/sec. Any effects of this motion cannot be eliminated unless acquisition windows are shorter than 33 msec.

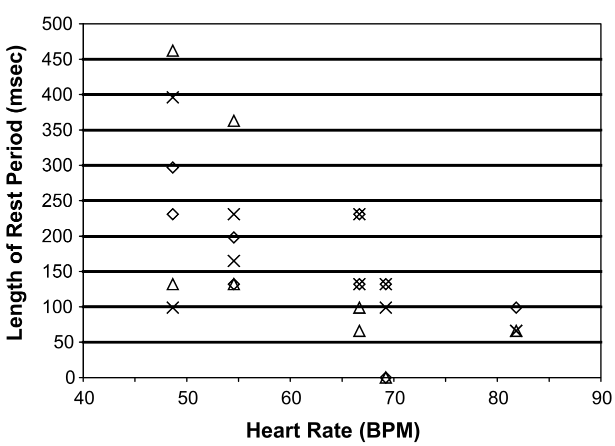

Figure 5. Heart rate (BPM) vs. length of rest period for the left anterior descending coronary artery. Periods of minimal displacement shorten as the heart rate increases. Graph shows the length of rest periods for proximal (◇), mid (△), and distal (×) regions of the vessel. One patient at 69 bpm did not exhibit a rest period in the proximal and midregions.

DISCUSSION

This study quantitatively describes the motion of the coronary arteries in three dimensions. The overall displacement of the RCA was 2.1±0.7 times that of the LAD and 2.1±1.5 times that of the LCX. Two periods in the cardiac cycle were seen in which all three coronary arteries have relatively little coronary motion (<1 mm/frame or 30 mm/sec). The first of these periods was located at the completion of ventricular systole (34±8% of the cardiac cycle) with duration of 118±78 msec. The temporal location of this rest period, however, varied significantly among the three coronary arteries. No acquisition window was able to capture the rest period of all segments of all arteries at the same time. A second period of low motion was seen at middiastole (72±5% of the cardiac cycle) with duration of 187±119 msec. This period was more consistent throughout the three coronary arteries and allowed for a window of 6% of the cardiac cycle during which, on average, all segments of the LAD, LCX, and RCA are ‘‘at rest.’’

It is important to note that our results represent averages across the collection of artery segments studied. There was significant variation between subjects. For example, a 100 msec acquisition window at 72% of the cardiac cycle would miss the period of low motion in 9 of 45 artery segments studied (3 segments had no diastolic rest period). Also in 9 of the artery segments, the rest period was only 66 msec. Any acquisition window or reconstruction window <66 msec will create some degree of blurring due to motion in these instances. When the allowed motion threshold was decreased to <0.5 mm/frame (15 mm/sec), the occurrence and duration of rest periods decreased substantially and did not allow for a single acquisition window to cover each artery segment.

The amount of motion varied along the length of the coronaries. In the right coronary artery, the midsegment of the vessel experienced 1.6 ± 0.4 times as much motion as that of the proximal region of the vessel. The distal segment of the LCX experienced 1.6 ± 0.8 times the motion as that of the proximal LCX. No significant variation in displacement was seen along the length of the LAD. Despite differences in amount of movement, the proximal, middle, and distal segments of all three coronaries still show the same temporal location of relative quiescence at end systole and in middiastole. Motion along anterior-posterior, right-left, and cranial-caudal axes also showed similar timing of rest periods. Most of the motion observed in the LAD and LCX occurred in the CC plane (59 ± 11% and 48–10%, respectively), whereas 48 ± 7% of the RCA motion occurred in the RL plane.

In the vast majority of vessel segments, the least motion and longest rest periods were observed in the proximal region of the three coronary arteries. This is arguably the most important region to image. Clinical studies have found that the largest percentage of stenotic lesions in the coronary arterial tree occur in the proximal regions of the arteries, most prevalently in the proximal LAD (Kyriakidis et al., 1995; Montenegro and Eggen, 1968). In addition, the larger amount of motion in the distal vessels as well as the smaller size of these vessels will make them more difficult to image.

Based on our results, current techniques to determine image acquisition timing in MR coronary angiography, such as using transverse cine imaging to visually locate periods of low motion, should not be adversely affected by through-plane motion because timing of rest periods in the cranial-caudal direction coincide with those in the in-plane (anterior-posterior and right-left) directions. For CT coronary angiography, where images are retrospectively reconstructed, we would suggest a reconstruction window of 60 msec centered around 72% of the cardiac cycle to produce images least affected by motion in most patients. Improvements in image acquisition or reconstruction must still be made in order to achieve such a temporal resolution over a wide range of heart rates. Results from this 3D motion study could also be used to generate physiological motion for theoretical or experimental studies of motion effects on coronary artery imaging.

During these periods of relatively little coronary motion, image quality of MR coronary angiography and coronary CT angiography should be least affected by motion artifacts. Image acquisition or reconstruction during this period in middiastole will have the best likelihood of producing images of diagnostic quality. However, there is a low level of coronary motion that remains and may affect image quality even if acquisition windows are short (<100 msec). Our analysis found this motion to be 7 mm/sec. Acquisition windows would have to be lower than 33 msec (the temporal resolution of x-ray cine angiography) to reduce the effects of this motion.

Despite a growing body of literature concerning coronary artery motion, results from these studies have varied and at times conflicted. Direct measurements of coronary artery motion have previously been performed by using magnetic resonance imaging (MRI) (Hofman et al., 1998; Kim et al., 2001; Wang et al., 1999), electron-beam CT (Achenbach et al., 2000b; Mao et al., 2000), and biplane cine angiograms (Ding and Friedman, 2000). Each of these studies and their imaging modalities has significant limitations. Although some MRI studies have excellent temporal resolution (22 ± 6 msec), the resultant image is an average of data obtained over multiple heartbeats and may not be an accurate representation of the true coronary motion. Electron-beam CT has a true temporal resolution of 58 msec, but poor spatial resolution (ranging from 0.4 mm^2 to 1.37 mm^2). The study by Wang et al. using cine angiograms was not synchronized with ECG readout, so no conclusions could be drawn regarding temporal location of rest periods—only that periods of decreased motion existed.

The studies using cross-sectional imaging techniques have reported similar patterns of coronary arterial movement in two dimensions during the cardiac cycle with velocity peaks during early systole and early diastole, motion of the RCA considerably greater than that of the LCX and LAD, and a high degree of variability among the patient population. Recommendations for optimal image acquisition time, however, have differed. Some findings have suggested acquiring during isovolumetric relaxation of the heart at approximately 35%–50% of the cardiac cycle (Achenbach et al., 2000b; Mao et al., 2000), whereas others recommend acquisition during mid-to-late diastole, 70%–80% of the cardiac cycle (Hofman et al., 1998; Kim et al., 2001). There are several possible explanations for these different findings. As mentioned earlier, temporal and spatial resolution varies greatly among the three imaging modalities used and could affect the results. Second, no standard definition of ''low motion'' has been set. Previous studies have either set arbitrary velocity thresholds (40 or 30 mm/sec) or vessel-specific thresholds defined as movement of a distance more than the vessel's diameter during one acquisition window (Lu et al., 2001). Differences in the studies' populations may also have played a role. Kim et al. studied healthy volunteers, whereas other studies recruited patients with suspected coronary disease. Gender distribution of the studies also ranged from 88% to 28% male. To our knowledge, no data exist comparing coronary motion between males and females, but significant gender differences in ventricular mass and stroke volume have been identified (Lorenz et al., 1999).

Our results suggest that mid-to-late diastolic image acquisition is better than acquisition during the earlier time period for the study of multiple artery segments in one scan, as is the case with multislice spiral computed tomography scans. A period of low motion was also seen around 30%–40% of the cardiac cycle, but the temporal location of this period differed substantially along the various segments of the LAD, LCX, and RCA. This is consistent with prior work (Lu et al., 2001; Vembar et al., 2003) that also reported larger interpatient variation in the timing of the end-systolic quiescent period than in the middiastolic period.

There were several limitations to this study. We only analyzed a small number (n=15) of angiography films in a fairly homogeneous population of patients with suspected CAD. Thus, we cannot predict how the location and duration of rest periods would vary in the larger, more diverse population. Also our patient group had relatively low heart rates (probably due to the majority of patients being on β-blockers). We are unable to draw conclusions on the effect of faster heart rates on the location of rest periods. Other research has suggested that the second rest period shortens in length or is eliminated altogether at heart rates greater than 70 beats per minute, especially in the right coronary artery (Lu et al., 2001). Although data from this population is well suited for diagnostic coronary angiography, it is possible that coronary artery motion patterns may differ in healthy hearts. If so, optimal image acquisition parameters for screening scans may differ from diagnostic scans. Further research with a larger patient population would be able to address these issues. We were also limited to observing cardiac motion in 33-msec increments due to the temporal resolution of the catheterization films. The selection of a 1-mm-per-frame threshold as our definition of low motion, although made for comparison with previous studies, was rather arbitrary. Further research is needed to determine what degree of motion begins to negatively impact clinical image quality in CT and MRI angiography. Finally, this study evaluated only cardiac motion and attempted to correct and eliminate any respiratory motion. In the clinical setting, respiratory motion can be as serious a problem as coronary motion. To optimize image quality, image acquisition during cardiac rest periods must be accompanied by established techniques such as breath-hold imaging or respiratory gating to minimize respiratory motion artifact.

In conclusion, we have traced the 3D motion of the left anterior descending, left circumflex, and right coronary arteries over the course of one heartbeat. The RCA demonstrated considerably more motion than the other two arteries and moved predominantly in the right-left plane. The predominant motion of the LAD and LCX was in the cranial-caudal plane. A period at 72% of the cardiac cycle was identified during which all three coronary arteries experienced low motion. This period was consistent along the length of the vessels but exhibited high interpatient variability.

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