Characterization of cardiac quiescence from retrospective cardiac computed tomography using a correlation-based phase-to-phase deviation measure

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Purpose: Accurate knowledge of cardiac quiescence is crucial to the performance of many cardiac imaging modalities, including computed tomography coronary angiography (CTCA). To accurately quantify quiescence, a method for detecting the quiescent periods of the heart from retrospective cardiac computed tomography (CT) using a correlation-based, phase-to-phase deviation measure was developed.

Methods: Retrospective cardiac CT data were obtained from 20 patients (11 male, 9 female, 33–74 yr) and the left main, left anterior descending, left circumflex, right coronary artery (RCA), and interventricular septum (IVS) were segmented for each phase using a semiautomated technique. Cardiac motion of individual coronary vessels as well as the IVS was calculated using phase-to-phase deviation. As an easily identifiable feature, the IVS was analyzed to assess how well it predicts vessel quiescence. Finally, the diagnostic quality of the reconstructed volumes from the quiescent phases determined using the deviation measure from the vessels in aggregate and the IVS was compared to that from quiescent phases calculated by the CT scanner. Three board-certified radiologists, fellowship-trained in cardiothoracic imaging, graded the diagnostic quality of the reconstructions using a Likert response format: 1 = excellent, 2 = good, 3 = adequate, 4 = nondiagnostic.

Results: Systolic and diastolic quiescent periods were identified for each subject from the vessel motion calculated using the phase-to-phase deviation measure. The motion of the IVS was found to be similar to the aggregate vessel (AGG) motion. The diagnostic quality of the coronary vessels for the quiescent phases calculated from the aggregate vessel (P_{AGG}) and IVS (P_{IVS}) deviation signal using the proposed methods was comparable to the quiescent phases calculated by the CT scanner (P_{CT}). The one exception was the RCA, which improved for P_{AGG} for 18 of the 20 subjects when compared to P_{CT} ($P_{CT} = 2.48$; $P_{AGG} = 2.07$, $p = 0.001$).

Conclusions: A method for quantifying the motion of specific coronary vessels using a correlation-based, phase-to-phase deviation measure was developed and tested on 20 patients receiving cardiac CT exams. The IVS was found to be a suitable predictor of vessel quiescence. The diagnostic quality of the quiescent phases detected by the proposed methods was comparable to those calculated by the CT scanner. The ability to quantify coronary vessel quiescence from the motion of the IVS can be used to develop new CTCA gating techniques and quantify the resulting potential improvement in CTCA image quality. © 2015 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4906246>]

Key words: cardiac computed tomography, cardiac gating, cardiac quiescence, cardiac motion, motion correction

1. INTRODUCTION

Cardiac quiescence during data acquisition is imperative to obtain diagnostic images of the coronary vessels for imaging modalities requiring extended data acquisition times, such as computed tomography (CT).¹ To minimize motion artifacts and blurring in cardiac images, it is necessary to acquire imaging data when the heart is relatively stationary, i.e., during quiescent periods within the cardiac cycle. Current methods for triggering acquisition rely almost exclusively on the electrocardiogram (ECG). However, the ECG serves only as a proxy for the mechanical state of the heart and has been shown to be imprecise in predicting quiescent phases due to subject and heart-rate variability.^{2,3} Therefore, it is desirable to detect and predict quiescence from a signal that is more indicative of cardiac motion. For this work, quiescent periods of the coronary vessels and interventricular septum (IVS) will be detected from retrospective cardiac CT data using two methods based on a robust correlation-based, phase-to-phase deviation measure. The results of this work will inform the development of more accurate methods for predicting cardiac quiescence based on signals derived directly from the mechanics of the heart, for example, using ultrasound or seismocardiography instead of solely the ECG.

The imaging performance of both cardiac CT and MRI relies heavily on triggering data acquisition during quiescent periods of the cardiac cycle, i.e., cardiac gating. Accurate gating is necessary to minimize motion artifacts and ensure that the heart is in the same position in the imaging plane for techniques requiring data acquisition over multiple cardiac cycles. One application where accurate gating is crucial is CT coronary angiography (CTCA).¹

CTCA is a promising alternative to the much more invasive catheter coronary angiography (CCA). More than 1.1×10^6 CCAs are performed annually in the United States of America resulting in more than 14 000 major complications and costing approximately $\$4 \times 10^9$ for the CCA alone.⁴ When hospital stay costs associated with CCA are included, this estimate can reach $\$40 \times 10^9$ annually. Furthermore, nearly 40% of these tests reveal no coronary artery disease (as defined by less than 20% vessel stenosis).⁵ Conversely, CTCA does not require catheterization and is, thus, a less invasive and more cost-effective alternative.

For this work, cardiac quiescence is estimated from retrospective cardiac CT studies. Reconstructions were obtained at 1% increments from 20% to 80% of the cardiac cycle for 20 subjects. Cardiac phase (%) is defined using the R–R interval of the ECG. For each reconstruction, five cardiac features are segmented using a semiautomated approach. The features include the IVS and the left main (LM), left anterior descending (LAD), left circumflex (LCX), and right coronary arteries (RCA). The IVS is segmented to compare IVS motion to that of the coronary vessels. Using a robust deviation measure based on the phase-to-phase correlation of each of these five cardiac features, the quiescence characteristics of the coronary vessels were investigated.

The objective of this paper is to provide a method for quantifying coronary vessel quiescence from cardiac CT. Quiescent

phases calculated using this method will be shown to have comparable diagnostic quality to those calculated by the CT scanner. Finally, the suitability of the IVS as a marker for coronary vessel quiescence will be demonstrated.

2. METHODS AND PROCEDURES

2.A. Data acquisition

Retrospective cardiac CT data were acquired from 20 human subjects (11 male, 9 female, 33–74 yr) using a Siemens Somatom Definition dual-source 64-slice CT scanner (Siemens, Erlangen, Germany). These subjects were examined independently of this study for various clinical indications and the data were collected retroactively with the approval of the Emory University Institutional Review Board (IRB). Informed consent requirement was waived by the IRB. CT volume reconstructions were created at 1% increments of the cardiac cycle from 20% to 80% based on the ECG signal used for gating during data acquisition.

2.B. Segmentation of cardiac features

Segmentation of the coronary vessel and IVS features is performed using a semiautomated approach wherein the feature is manually segmented for an undersampled number of axial slices containing the feature, i.e., each manually segmented slice is separated by several nonmanually segmented slices. The manual segmentations were performed by a graduate researcher under the guidance of a radiologist. The segmentations of the feature for the remaining slices are calculated using an interpolation scheme based on the signed distance function (SDF) of the two neighboring, manually segmented slices. The final three-dimensional (3D) segmentation is then constructed by combining all of the segmented slices. This process is shown in Fig. 1 where $z_{\min}$ and $z_{\max}$ are the superior and inferior boundaries in the craniocaudal direction of the feature to be segmented. Black lines indicate slices that are manually segmented and gray lines indicate slices that are segmented using SDF interpolation.

The pixels defining the location of the feature in a given slice form a set S . The SDF of S is defined as

$$\phi_S(x, y) = \begin{cases} d_S(x, y) & \text{if } (x, y) \in S \\ -d_S(x, y) & \text{if } (x, y) \notin S \end{cases} \quad (1)$$

where $d_S(x, y)$ is the Euclidean distance from the point (x, y) to the nearest point on the boundary of S . It follows that $\phi_S(x, y)$ will be zero on the boundary of S and greater than zero inside S .

The segmentations of the nonmanually segmented slices are interpolated from the SDF of the two nearest-neighboring, manually segmented slices. Note that the manually segmented slices may have more than one slice between them. Let $\phi_{S_z}(x, y)$ be the SDF for the axial slice at height z . The slice interpolation scheme is then defined as

$$\phi_{S_z}(x, y) = \frac{(z^+ - z)\phi_{S_{z^-}} + (z - z^-)\phi_{S_{z^+}}}{z^+ - z^-}, \quad z^- < z < z^+, \quad (2)$$

FIG. 1. Depiction of semiautomated segmentation setup. Black lines indicate slices that are manually segmented and gray lines indicate slices that are segmented using SDF interpolation.

where z^- and z^+ are the heights of the proximal superior and inferior manually segmented slices in the craniocaudal direction, respectively. The segmentation for each slice at a height z is then defined as the set of points, (x, y) , where $\phi_{S_z}(x, y)$ is greater than or equal to zero, i.e.,

$$\{S_z \in \mathbb{R}^2 : S_z = (x, y), \phi_{S_z}(x, y) \geq 0\}. \quad (3)$$

The final 3D segmentation, V , is obtained by combining all of the segmented slices, i.e.,

$$\{V \in \mathbb{R}^3 : V = (x, y, z), z_{\min} \leq z \leq z_{\max}, (x, y) \in S_z\}, \quad (4)$$

where $z_{\min}$ and $z_{\max}$ are the superior and inferior boundaries of the cardiac feature in the craniocaudal direction.

2.C. Identification of intrafeature cardiac quiescent periods

Quiescent periods of the coronary vessels and the IVS are calculated using a correlation-based, phase-to-phase deviation measure. In short, the deviation between a segmented feature at a given cardiac phase and neighboring phases is computed. This deviation measure will decrease as the cardiac feature becomes more quiescent.

For this work, the deviation between cardiac phases is expressed as a negative function of the Pearson correlation coefficient taken over the feature volume. This method is a 3D analog to the method proposed to analyze cardiac quiescence from echocardiography.⁶ The Pearson correlation coefficient has been shown to be a strong indicator of image similarity and as such can be interpreted as a measure of the similarity of the feature position between two phases.⁷ The correlation coefficient between two phases, i and j , over a volume, V , is given as

$$\rho_V(i, j) = \frac{\sum_{(x, y, z) \in V} (I_i(x, y, z) - \bar{I}_i^V)(I_j(x, y, z) - \bar{I}_j^V)}{\sqrt{\sum_{(x, y, z) \in V} (I_i(x, y, z) - \bar{I}_i^V)^2 \sum_{(x, y, z) \in V} (I_j(x, y, z) - \bar{I}_j^V)^2}}, \quad (5)$$

where I_i is the imaged volume at phase i , and $\bar{I}_i^V$ is the mean of I_i in V .

Here, a static volume, V_S , is chosen to be the union of the segmentations for all phases and is defined as

$$V_S = \bigcup_i V_i, \quad (6)$$

where V_i is the set of voxels in $\mathbb{R}^3$ indicating the segmentation for cardiac phase i . This choice of V_S provides the smallest set containing the segmentations of all phases.

The phase-to-phase deviation is calculated as

$$\mathbf{D}(i, j) = 1 - \rho_{V_S}(i, j) \quad (7)$$

for all possible phase-to-phase pairs. The resulting *deviation matrix* for a specific vessel can then be viewed as an image allowing for the quiescent phases to be readily identified visually. An example of $\mathbf{D}(i, j)$ for the LM, LAD, LCX, and RCA of Subject 2 viewed as images is shown in Fig. 2 with blue regions along the diagonal corresponding to matching phases and hence quiescent periods.

2.C.1. Aggregate vessel (AGG) deviation

To investigate the motion of the coronary vessels taken in aggregate for each subject, a deviation matrix is formed from the union of the four static volumes representing the LAD, LM, LCX, and RCA found using Eq. (6). That is, the aggregate deviation for all vessels for each subject is defined as

$$\mathbf{D}_{\text{AGG}}(i, j) = 1 - \rho_{V_{\text{AGG}}}(i, j), \quad (8)$$

where V_{AGG} is the union of all vessel segmentations for a given subject.

2.C.2. Quiescence from approximated velocity

The magnitude of the velocity of the vessel in the direction orthogonal to the primary axis of the vessel is approximately proportional to the phase-to-phase deviation. This holds because the value of $\mathbf{D}(i, j)$ is approximately linear with vessel displacement in the orthogonal direction. This approximation holds as long as between phases i and j the vessel is cylindrical, does not deform, moves linearly, and is displaced less than the feature radius. Because the phase delay between neighboring cycles is only 1%, the velocity magnitude can be approximated by the deviation between sequential phases defined as

$$v_{\text{app}}(i) = \mathbf{D}(i, i-1), \quad (9)$$

where $v_{\text{app}}(i)$ is the approximated velocity of the vessel at phase i , and $\mathbf{D}(i, i-1)$ is the one-off diagonal of the deviation matrix.

FIG. 2. Deviation matrices for the LAD, LM, LCX, and RCA of Subject 2. Low deviation (blue) corresponds to minimal motion between phases while high deviation (red) corresponds to greater motion. Therefore, blue regions along the diagonal correspond to quiescent periods. The one-off diagonal, $\mathbf{D}(i, i - 1)$, is indicated by a dashed white line on the deviation matrix of the LM.

For this work, quiescent periods are defined from the velocity approximation as phases of the cardiac cycle when $v_{app}(i)$ is less than the mean of $v_{app}(i)$. This choice was made to ensure that each vessel was thresholded in a comparable manner. An example of this process for the LM of Subject 2 is provided in Fig. 3.

2.C.3. Quiescent phases and the deviation signal

Ideally, the acquisition time of the CT scanner should be taken into account in identifying quiescent phases. This is accomplished by finding the minimum of an averager operating on a square neighborhood sliding along the diagonal of $\mathbf{D}(i, j)$. The mean of the square neighborhood corresponds

to the similarity of the consecutive phases that make up the neighborhood. The size of the square neighborhood is chosen to correspond to the data acquisition time of the CT scanner. For this work, the acquisition time is 83 ms, corresponding to the quarter gantry rotation time taken by a dual-source CT scanner with a rotation time of 333 ms. As an example, for a subject with a heart rate of 60 bpm, 1% of the cardiac cycle will equal 10 ms. Therefore, a neighborhood covering 8% will approximately cover the 83 ms necessary for data acquisition. By finding the neighborhood with the minimum mean deviation, the most quiescent phase is found. The output of the moving averager, called the *deviation signal*, can be expressed as

$$d(i) = \frac{1}{N^2} \sum_{n_1=-N/2}^{N/2} \sum_{n_2=-N/2}^{N/2} \mathbf{D}(i + n_1, i + n_2), \quad (10)$$

where N is the width of the neighborhood. A graphical representation of this idea is provided by Fig. 4 where the moving averager operating on $\mathbf{D}(i, j)$ and the resulting $d(i)$ are shown for the LM of Subject 2. Note that the deviation signal is a smoothed version of the approximated velocity shown in Fig. 3.

2.D. Diagnostic quality of quiescent phases

The diagnostic quality of the quiescent phases determined from the deviation signal as described in Sec. 2.C.3 was compared to that of the quiescent phases calculated by the CT scanner. Quiescent phases were determined for each of

FIG. 3. Normalized approximated velocity of the LM for Subject 2 with the systolic and diastolic quiescent periods indicated. The threshold for quiescence is chosen to be the mean of the approximated velocity signal, indicated in the figure by the dashed line.

FIG. 4. Deviation matrix for the LM of Subject 2 showing the moving averager operating on a square neighborhood with a size corresponding to 83 ms. The normalized output of the moving averager, $d(i)$, is shown in (b).

the 20 subjects from both the AGG and IVS deviation signals, P_{AGG} and P_{IVS} , respectively. The IVS-selected quiescent phases are included to facilitate the investigation of IVS quiescence as a proxy for coronary vessel quiescence and hence diagnostic quality. Quiescent phases identified by the CT scanner, P_{CT} , were determined by the proprietary Siemens BestPhase algorithm.⁸ The diagnostic quality of the LM, LAD, LCX, and RCA was graded for P_{CT} , P_{AGG} , and P_{IVS} through an observer study by three board-certified radiologists who are fellowship-trained in cardiothoracic radiology. The studies were presented in random order and the radiologists were blinded to the source of the reconstructions, i.e., the radiologist did not know whether the reconstructions were from the phases obtained by the methods presented in this work (P_{AGG} and P_{IVS}) or the phases calculated by the CT scanner (P_{CT}). The diagnostic quality of the reconstructions for the proximal segments of each of the four vessels was graded using a four-point Likert response format (1 = excellent: no motion artifacts, clear delineation of segment; 2 = good: minor artifacts, mild blurring of segment; 3 = adequate: moderate artifacts, moderate blurring without structure discontinuity; 4 = not evaluative: discontinuity of segment preventing evaluation or vessel structures not differentiable). A two-sided Wilcoxon signed-rank test was performed to assess the validity of the observed difference between the diagnostic quality of the quiescent phases determined from the deviation signal and those calculated by the CT scanner. A p -value of less than 0.05

was considered to be statistically significant. Interobserver agreement was measured using Fleiss' Kappa value.

2.E. Comparison of interfeature cardiac quiescence

The similarity of the deviation signals from Sec. 2.C.3 is found using a weighted correlation technique to compare the $d(i)$ for pairs of features. The correlation used is a modification of the standard Pearson correlation measure that is weighted more heavily in regions where $d(i)$ is smaller, i.e., more quiescent. The weighted correlation is defined as

$$\rho_w(d_x, d_y) = \frac{\sum_n w(n)(d_x(n) - \bar{d}_x)(d_y(n) - \bar{d}_y)}{\sqrt{\sum_n w(n)(d_x(n) - \bar{d}_x)^2 \sum_n w(n)(d_y(n) - \bar{d}_y)^2}}, \quad (11)$$

where d_x and d_y are the deviation signals of the two features, w is the weighting vector, and $\bar{d}$ is the weighted mean of d . For this work, the weight vector is defined as the normalized distance from the maximum to the minimum of the average of d_x and d_y . This can be expressed as

$$w(i) = \frac{\hat{d}_{\max} - \hat{d}(i)}{\hat{d}_{\max} - \hat{d}_{\min}}, \quad (12)$$

where $\hat{d}(i) = (d_x(i) + d_y(i))/2$, and $\hat{d}_{\min}$ and $\hat{d}_{\max}$ are the minimum and maximum of $\hat{d}(i)$, respectively. This choice of weighting vector results in $w = 0$ for $\hat{d}(i) = \hat{d}_{\max}$ and $w = 1$ for $\hat{d}(i) = \hat{d}_{\min}$. An example of the deviation signals for the IVS and the aggregate vessel motion is given in Fig. 5. The two signals are normalized to have zero mean and unit power, and have a weighted correlation of 0.88.

3. RESULTS

The reconstructed CT volumes for each of the 20 subjects were segmented and the motion of the LM, LAD, LCX, RCA, and IVS was investigated. The approximated velocity magnitude of each of the cardiac features was found and used to identify the center and duration of the quiescent periods of each feature. The most quiescent phase for each vessel,

FIG. 5. Deviation signals for the IVS and aggregate vessel motion, normalized to have zero mean and unit power. The two signals have a weighted correlation of 0.88 calculated from Eq. (11).

the vessels in aggregate, and the IVS were found from the corresponding deviation signals using the method described in Sec. 2.C.3. The deviation signal comparison technique described in Sec. 2.E was then used to determine if the IVS is a suitable predictor of aggregate vessel quiescence. Finally, the diagnostic quality of the quiescent phases calculated by the CT scanner was compared to those determined from the AGG and IVS deviation signals.

3.A. Segmentation of the coronary vessels and interventricular septum

The LM, LAD, LCX, RCA, and IVS were segmented using the approach outlined in Sec. 2.B. The average ratio of total number of segmented slices to the number of manually segmented slices was three and eight for the coronary vessels and IVS, respectively. These ratios indicate the overall segmentation speedup achieved by using the proposed method, rather than manually segmenting each slice.

3.B. Identification of quiescent periods for the coronary vessels and the interventricular septum

3.B.1. Center and duration of quiescent periods

The center and duration of the systolic and diastolic quiescent periods of the LM, LAD, LCX, RCA, and IVS were calculated using the method described in Sec. 2.C.2. The systolic quiescent period was defined as the longest quiescent phase

with a center occurring before 60% of the cardiac cycle as defined by the R–R interval of the ECG. The diastolic quiescent period was defined in the same manner but with a center occurring at or later than 60%. The results of these calculations are shown in Fig. 6 where the systolic and diastolic quiescent periods for each of the 20 subjects are plotted against the heart rate of the subject.

From Fig. 6, the position and duration of the quiescent phases exhibit a large amount of intersubject variability. This suggests that the ECG alone may be suboptimal in terms of predictive accuracy of cardiac quiescence.

The subjects were separated into low (below 65 bpm), medium (from 65 to 85 bpm), and high (above 85 bpm) heart-rate ranges. There were six subjects with low heart rates, six with medium heart rates, and eight with high heart rates. The tabulated results of each vessel for each range are provided in Table I.

From Fig. 6 and Table I, the duration of the systolic phases in terms of percent of the cardiac cycle can be seen to increase with heart rate, while that of the diastolic phases can be seen to decrease with heart rate. This agrees with the accepted standard that at higher heart-rates cardiac imaging data should be obtained during systole.¹

3.B.2. Quiescent phases from the deviation signal

The quiescent phase of each coronary vessel, the vessels in aggregate, and the IVS were determined from the

FIG. 6. Quiescent periods of the LM, LAD, LCX, RCA, coronary vessels taken in aggregate, and IVS for 20 subjects. The centers of the systolic and diastolic quiescent periods are marked with squares and circles, respectively. The durations of the quiescent periods are indicated by the length of the lines extending from the period centers. Note that not every patient had both a systolic and diastolic quiescent period.

TABLE I. Quiescent period statistics.

HR (bpm)	Feature	Systolic periods		Diastolic periods	
		Center (%)	Duration (ms)	Center (%)	Duration (ms)
Low					
(<65)	LM	36.2 ± 4.1	151.8 ± 47.3	73.9 ± 2.7	212.5 ± 56.6
	LAD	35.2 ± 2.1	182.9 ± 50.0	73.2 ± 3.3	197.4 ± 78.2
	LCX	38.1 ± 5.5	171.6 ± 61.4	74.0 ± 4.1	210.8 ± 81.3
	RCA	39.7 ± 4.9	146.3 ± 44.4	75.1 ± 1.1	192.0 ± 27.3
	AGG	39.4 ± 4.7	160.9 ± 77.4	74.7 ± 3.1	200.7 ± 62.1
	IVS	36.1 ± 1.5	137.7 ± 35.1	74.4 ± 1.4	205.0 ± 29.8
Medium					
(65–85)	LM	43.6 ± 3.4	139.0 ± 46.5	76.7 ± 2.0	145.9 ± 34.2
	LAD	38.9 ± 3.6	144.4 ± 59.2	76.6 ± 2.4	146.8 ± 39.9
	LCX	43.7 ± 2.3	132.6 ± 39.1	75.6 ± 1.4	159.1 ± 24.3
	RCA	42.4 ± 3.9	181.6 ± 53.0	78.0 ± 1.0	118.7 ± 25.4
	AGG	41.7 ± 2.3	151.2 ± 33.3	77.2 ± 0.8	135.8 ± 19.2
	IVS	40.9 ± 5.1	138.0 ± 33.6	76.8 ± 1.3	143.3 ± 18.0
High					
(>85)	LM	44.8 ± 4.3	149.0 ± 34.3	74.7 ± 4.2	49.1 ± 36.8
	LAD	43.6 ± 6.3	151.6 ± 43.0	76.5 ± 4.5	42.4 ± 28.4
	LCX	43.8 ± 6.7	146.3 ± 55.8	77.4 ± 5.5	47.8 ± 43.0
	RCA	44.1 ± 4.9	163.5 ± 36.8	76.9 ± 5.4	44.4 ± 37.7
	AGG	45.1 ± 5.0	165.0 ± 35.8	76.1 ± 5.1	42.0 ± 45.4
	IVS	42.5 ± 6.1	122.3 ± 39.1	80.7 ± 4.5	61.5 ± 58.4

corresponding deviation signals for all 20 subjects. This was accomplished by determining the minimum of the deviation signal $d(i)$ as defined in Eq. (10). The subjects were separated into low, medium, and high heart-rate ranges, as before. A summary of the statistics is provided in Table II. Note that a high standard deviation for a given heart-rate range corresponds to some phases being in systole and some in diastole. This is most apparent for medium heart rates (from 65 to 85 bpm) because the quiescent phase transitions from diastole to systole in this heart-rate range.

An interesting conclusion that can be drawn from Table II is that the quiescent phase of the RCA transitions to systole at a lower heart rate than the other vessels and that the quiescent phase of the IVS transitions to systole at a higher heart rate than the coronary vessels. Also of note is that the quiescent

phase of the vessels when taken in aggregate is very similar to each individual vessel with the exception of the RCA.

3.C. Interfeature comparison of deviation signals

The deviation signals for each cardiac feature were compared for all subjects using the weighted correlation technique described in Sec. 2.E. In addition to comparing each feature to every other feature, the IVS was compared to the aggregate deviation signal representing all vessels. This comparison was performed in order to observe the similarity of the deviation signal of the IVS to the coronary vessels taken as a whole. Prior to calculating the weighted correlation, all signals were normalized to have zero mean and unit power. The summary of the comparison is presented in Table III with the subjects separated into low, medium, and high heart-rate ranges as described in Sec. 3.B.1. An example of two deviation signals with a weighted correlation of 0.83 is provided in Fig. 5.

The similarity of the deviation signals tends to decrease as heart rate increases, with the deviation signals of subjects with low heart rates being very similar. In addition, the IVS tends to be more similar to the deviation signal representing aggregate vessel motion than the deviation signals representing each individual vessel. This suggests that the IVS is a better predictor for aggregate vessel motion than for specific vessel motion. The deviation signal of the IVS is least similar to that of the RCA.

TABLE II. Statistics of quiescent phases determined from the deviation signal (%).

	Low HR (<65 bpm)	Medium HR (65–85 bpm)	High HR (>85 bpm)
LM	78.2 ± 1.7	67.5 ± 15.4	45.3 ± 5.3
LAD	76.9 ± 2.7	71.8 ± 14.8	43.9 ± 6.7
LCX	71.7 ± 13.3	71.8 ± 13.8	45.9 ± 9.6
RCA	71.6 ± 12.3	51.0 ± 13.2	46.6 ± 5.9
AGG	71.7 ± 15.9	72.7 ± 13.6	45.9 ± 3.0
IVS	79.1 ± 1.8	79.8 ± 1.5	59.0 ± 16.2

TABLE III. Average correlations of deviation signals.

Low heart rate (<65 bpm)						
	LM	LAD	LCX	RCA	AGG	IVS
LM	1.00	0.92	0.89	0.82	0.91	0.87
LAD	—	1.00	0.85	0.79	0.85	0.83
LCX	—	—	1.00	0.76	0.91	0.82
RCA	—	—	—	1.00	0.86	0.82
AGG	—	—	—	—	1.00	0.84
IVS	—	—	—	—	—	1.00
Medium heart rate (65–85 bpm)						
Medium HR	LM	LAD	LCX	RCA	AGG	IVS
LM	1.00	0.83	0.91	0.76	0.90	0.77
LAD	—	1.00	0.87	0.61	0.84	0.78
LCX	—	—	1.00	0.73	0.92	0.76
RCA	—	—	—	1.00	0.85	0.67
AGG	—	—	—	—	1.00	0.81
IVS	—	—	—	—	—	1.00
High heart rate (>85 bpm)						
High HR	LM	LAD	LCX	RCA	AGG	IVS
LM	1.00	0.65	0.75	0.68	0.86	0.63
LAD	—	1.00	0.72	0.51	0.67	0.53
LCX	—	—	1.00	0.59	0.79	0.78
RCA	—	—	—	1.00	0.86	0.57
AGG	—	—	—	—	1.00	0.64
IVS	—	—	—	—	—	1.00

Note: dashes represent symmetric entries about the diagonal.

3.D. Comparison of quiescent phases calculated by the CT scanner and those identified from the deviation signal

The quiescent phases of the AGG and IVS deviation signals were compared to the nearest systolic or diastolic quiescent phase calculated by the CT scanner for each subject. The results of this comparison for P_{CT} and P_{AGG} are shown in Fig. 7. The average absolute difference in terms of phase is 5.1%. Figure 7 also shows that there is no bias toward under- or overprediction and that the calculated phases are more variable than those detected from the deviation signal.

To quantify the effect that this discrepancy in prediction has on diagnostic quality, the CT reconstructions corresponding to each of the P_{CT} , P_{AGG} , and P_{IVS} (60 in total) were read by three practicing radiologists. The diagnostic quality of the LM, LAD, LCX, and RCA was graded on a scale from one (excellent) to four (nondiagnostic). The radiologists had a Fleiss' Kappa value of 0.329. The average diagnostic quality grade along with the Wilcoxon signed-rank test p -value for each segment when compared to P_{CT} is given in Table IV. In general, the phases calculated according to the method presented in Sec. 2.C.3 were of comparable diagnostic quality as those calculated by the CT machine. One exception was the diagnostic quality of the RCA, which improved for P_{AGG} when compared to P_{CT} for 18 of the 20 studies. An example of a study that went from nondiagnostic to diagnostic for

Fig. 7. Comparison of the phases calculated by the CT machine (P_{CT}) to the quiescent phases determined from the AGG deviation signal (P_{AGG}) for each subject. P_{CT} and P_{AGG} are indicated by squares and circles, respectively.

both the LCX and RCA is shown in Fig. 8. In addition, the diagnostic quality of P_{IVS} was comparable to that of P_{AGG} further suggesting that the IVS is a suitable indication of vessel motion.

4. DISCUSSION

To better understand cardiac quiescence, a method for robustly quantifying the cardiac quiescence of specific cardiac features from cardiac CT reconstructions was developed. This method is based on a deviation measure calculated from the phase-to-phase correlation of each cardiac feature. Understanding cardiac quiescence is critical to the performance of many cardiac imaging modalities, including CTCA, that rely on acquiring imaging data while the heart is relatively stationary.

To analyze the quiescence of the LM, LAD, LCX, RCA, and IVS, a semiautomated method was developed to segment each cardiac feature. An undersampled number of axial slices were manually segmented. The segmentations for the missing slices were then interpolated from the neighboring manually segmented slices. When compared to manually segmenting each slice, this approach resulted in an average speedup by a factor of 3 for the coronary vessels and 8 for the IVS. A semiautomated approach to segmentation was needed because reconstructions containing motion artifacts would prove problematic for a completely automated approach. In general,

TABLE IV. Diagnostic quality grades averaged across three readers for each coronary vessel.

	P_{CT}	P_{AGG} (p -value)	P_{IVS} (p -value)
LM	1.20	1.22 (1.000)	1.18 (0.766)
LAD	2.25	2.38 (0.327)	2.23 (0.867)
LCX	2.52	2.38 (0.454)	2.37 (0.338)
RCA	2.48	2.07 (0.001)	2.45 (0.242)
Mean	2.11	2.01 (0.189)	2.04 (0.249)

Note: grade: 1 = excellent, 2 = good, 3 = adequate, 4 = nondiagnostic, p -values calculated against P_{CT} .

FIG. 8. Comparison of the diagnostic quality of the RCA and LCX for the CT scanner calculated quiescent phase [(a), (c), and (e)] and the quiescent phase calculated from the AGG deviation signal [(b), (d), and (f)].

when automated vessel segmentation is attempted, it is performed at predetermined phases that are free from motion artifacts.⁹

The coronary vessels and the IVS were investigated for 20 patients. The systolic and diastolic quiescent periods were found to be similar across cardiac features. The statistics of the quiescent periods showed a dependency on subject heart rate. This was most notable for the duration of the diastolic quiescent period, which was much shorter for high heart rates (above 85 bpm). As can be seen from Table I, the longest quiescent phase transitions from diastole to systole as heart rate increases. This is in line with the accepted consensus that the optimal gating window occurs in diastole for low heart rates and systole for high heart rates.^{10,11}

The quiescent phase of each coronary vessel, the vessels taken in aggregate, and the IVS were detected by finding the most quiescent period with a length of 83 ms. This duration corresponds to the minimum acquisition time of the CT scanner used for this work. The quiescent phase of the RCA was found to transition from diastole to systole at a lower heart rate than the other coronary vessels. On the other hand, the quiescent phase of the IVS was found to transition at a higher heart rate than the coronary vessels.

Advanced CT reconstruction methods are another approach to improving image quality in the presence of cardiac motion.^{12,13} Furthermore, algorithms that correct for motion during reconstruction are becoming clinically available.^{14,15} Even when using these techniques, it is still prudent to avoid as

much motion during acquisition as possible. Thus, the results and methods presented in this work can supplement advanced reconstruction techniques.

For each subject, the coronary vessels, the vessels taken in aggregate, and the IVS were compared to observe the overall motion similarity among the different cardiac features. The similarity between the features was high for low heart rates and decreased as heart rate increased. The motion of the IVS was found to be more similar to the aggregate vessel motion than the motion of individual vessels, suggesting that the IVS is a better predictor of aggregate vessel motion than for specific vessel motion.

The quiescent phase of the coronary vessels taken in aggregate was compared against the calculated best phase by the CT scanner for each subject. The phases calculated by the CT scanner were found to differ from those determined from the proposed methods by an average of 5.1% in terms of absolute phase difference. Also, this discrepancy showed no positive or negative bias and did not trend with heart rate. These results suggest that there is room for improvement in predicting cardiac quiescence for the purpose of gating cardiac CT acquisition.

The IVS was found to be a suitable predictor of vessel quiescence, especially for aggregate vessel quiescence. Aggregate vessel quiescence is most important in terms of cardiac imaging, as it is typically desired to diagnose all coronary vessels from one exam. Liu *et al.* showed that the IVS was an accurate predictor of LAD vessel quiescence.¹⁶ From Table III, the LAD is in fact among the least similar to the IVS, suggesting that if the IVS is a suitable predictor for the LAD it will be as good or better for the other vessels. The quiescence of the IVS is of particular interest because it can be readily observed using echocardiography, as opposed to the coronary vessels. The use of echocardiography to analyze cardiac quiescence is extremely useful because it is a real-time visualization of cardiac motion. This correlation between the IVS and the coronary vessels suggests that echocardiographic evaluation of the IVS can be used to analyze cardiac quiescence on a beat-by-beat basis.⁶ Thus, echocardiography could potentially form the basis of a real-time gating technique by tracking IVS motion.

4.A. Limitations

The principal limitation of the proposed methods is the time necessary to perform the coronary vessel segmentations. Though only every third slice was manually segmented, the process would be difficult to implement clinically. This work showed that the motion of the IVS was a suitable proxy for vessel motion and diagnostic quality, suggesting that segmentation of the IVS alone may be sufficient for determining vessel quiescence. This is important because the IVS of a given CT reconstruction requires approximately 11 times fewer manually segmented slices than the four coronary vessels included in this work. However, it is still important to stress that the proposed methods are primarily intended as an investigatory tool for cardiac quiescence and as such have been shown to be effective.

Additionally, the performance of the segmentation interpolation scheme suggested in this work is largely dependent on both the geometry of the feature being segmented and the ratio of the number of manually segmented slices to interpolated slices, e.g., the IVS requires fewer manually segmented slices than the more tortuous coronary vessels. Potential errors in interpolation can arise if too few manual segmentations are made. For this work, the number and position of the manually segmented slices were chosen by visually observing the geometry of the feature to be segmented. Also, the approach presented in this work is robust to errors in segmentation because the correlation was taken over the union of all segmentations. Because of the nature of using correlation as a proxy for velocity, the static volume formed from the union of individual phase segmentations is primarily intended to exclude unwanted features from the region of interest rather than tightly bound the segmented feature.

Another limitation of this work is that the CT reconstructions used only covered the range of 20%–80% of the cardiac cycle. This range of the cardiac cycle was chosen because it has been shown to contain the optimal systolic and diastolic quiescent phases.^{3,17} However, since the remainder of the cardiac cycle, i.e., between 80% and 20% is not reconstructed, it is possible that the start of the systolic or end of the diastolic quiescent period may lie outside the 20%–80% reconstructed interval of the cardiac cycle. This is apparent in Fig. 6, where a number of quiescent periods begin either at 20% or end at 80%. This may explain the difference between the phase of the quiescent period centers and the quiescent phases determined from the deviation signal. An artificially truncated quiescent period will be biased away from the boundaries of the reconstructed interval. This is because each quiescent period center is defined as the midpoint between the beginning and end of that quiescent period. On the other hand, the method used to determine the quiescent phase from the deviation signal is independent of the beginning and end phase of the quiescent period.

Finally, by observing motion directly from CT reconstructions, beat-to-beat heart-rate variability is not taken into account. This is because the CT reconstructions are created from data acquired over multiple cardiac cycles. Observing intrasubject variability is important to understand how it affects diagnostic quality. It has been shown that as heart-rate variability increases the diagnostic image quality decreases.¹⁸ For this reason, it is also important to observe quiescence on a beat-by-beat basis, suggesting that echocardiography and other signals derived directly from cardiac motion will be complementary in the analysis and prediction of cardiac quiescence.

4.B. Conclusion

A robust approach for identifying and analyzing cardiac quiescence from retrospective cardiac CT scans was developed. The center and duration of the quiescent periods were found and the quiescent phases were computed for each subject. The calculated best reconstruction phases by the CT scanner were found to differ from the quiescent phases determined from the deviation signal by 5% in terms of absolute phase.

The diagnostic quality of the quiescent phases found using the proposed methods was found to be comparable to that of those calculated by the CT machine. Finally, the IVS was found to be a suitable predictor of vessel quiescence, suggesting the applicability of echocardiography as a tool for observing quiescence on a beat-by-beat basis.

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