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## Echocardiography as an indication of continuous-time cardiac quiescence

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### Abstract

Cardiac computed tomography (CT) angiography using prospective gating requires that data be acquired during intervals of minimal cardiac motion to obtain diagnostic images of the coronary vessels free of motion artifacts. This work is intended to assess B-mode echocardiography as a continuous-time indication of these quiescent periods to determine if echocardiography can be used as a cost-efficient, non-ionizing modality to develop new prospective gating techniques for cardiac CT. These new prospective gating approaches will not be based on echocardiography itself but on CT-compatible modalities derived from the mechanics of the heart (e.g., seismocardiography and impedance cardiography), unlike the current standard electrocardiogram. To this end, echocardiography and retrospectively-gated CT data were obtained from 10 patients with varied cardiac conditions. CT reconstructions were made throughout the cardiac cycle. Motion of the interventricular septum (IVS) was calculated from both echocardiography and CT reconstructions using correlation-based, deviation techniques. The IVS was chosen because it 1) is visible in echocardiography images, whereas the coronary vessels generally are not, and 2) has been shown to be a suitable indicator of cardiac quiescence. Quiescent phases were calculated as the minima of IVS motion and CT volumes were reconstructed for these phases. The diagnostic quality of the CT reconstructions from phases calculated from echocardiography and CT data was graded on a four-point Likert scale by a board-certified radiologist fellowship-trained in cardiothoracic radiology. Using a Wilcoxon signed-rank test, no significant difference in the diagnostic quality of the coronary vessels was found between CT volumes reconstructed from echocardiography- and CT-selected phases. Additionally, there was a correlation of 0.956 between the echocardiography- and CT-selected phases. This initial work suggests that B-mode echocardiography can be used as a tool to develop CT-compatible gating techniques based on modalities derived from cardiac mechanics rather than relying on the ECG alone.

## Keywords

Echocardiography; Computed Tomography; Angiography; Cardiac Quiescence; Cardiac Gating

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## 1. Introduction

Catheter coronary angiography (CCA), which has exquisite temporal and spatial resolution, is the gold standard for the evaluation of coronary artery disease. However, CCA is expensive and invasive, with a non-negligible rate of complications (Applegate et al. 2008, Roger et al. 2012). More importantly, approximately 40% of the CCA examinations reveal no coronary artery disease, raising the concern that many patients who undergo diagnostic CCA could avoid this invasive test if a less invasive alternative were available to evaluate the coronary arteries (Patel et al. 2010).

Coronary computed tomography angiography (CTA) is an emerging alternative to CCA because it is a non-invasive and less expensive approach to evaluate coronary arteries. However, CTA is limited by its temporal resolution. The time necessary to acquire sufficient CT data for slice reconstruction is at least 66–83 ms for dual-source CT scanners and at least 140–166 ms for single-source CT scanners. Therefore, to obtain diagnostic images of the coronary vessels with minimized motion artifacts, CT slice acquisition for CTA needs to be triggered, or *gated*, when the heart is in the relatively quiescent phases within the cardiac cycle.

CTA gating is usually approached either prospectively or retrospectively based on electrocardiogram (ECG) signals (Desjardins & Kazerooni 2004). For prospective gating, the CT tube current is turned ON only during the ECG-predicted quiescent phases within the cardiac cycle. The drawback with prospective gating is that if the prediction of quiescence is not accurate, then the diagnostic quality of the reconstructions of the coronary arteries is compromised. On the other hand, for retrospective gating, the tube current remains ON throughout the entire ECG R-R interval. The quiescent phases are then selected retrospectively in order to obtain only those coronary artery reconstructions that minimize motion. Because data on coronary arteries are available from all phases in the cardiac cycle, retrospective gating is more likely to provide diagnostic studies than prospective gating. However, the drawback with retrospective gating is the increased radiation (10–15 mSv) relative to prospective gating (3–4 mSv) (Menke et al. 2013). Thus it is necessary to balance the trade-off between exposure and diagnostic image quality.

Although ECG remains the standard gating method, it suffers an inherent inaccuracy for determining quiescence. Since there is some variability between the electrical activity of the heart provided by the ECG and the mechanical motion of the heart, quiescence predicted by electrical activity does not consistently translate to quiescence in mechanical motion (Vembar et al. 2003). Guided by this understanding, we have explored echocardiography, which can provide real-time information of cardiac motion, as a tool to develop cardiac-motion-based alternatives to ECG-based gating for CTA. Quiescence of the interventricular septum (IVS), which is readily visible on echocardiography and CT, has been shown to be reliable predictor of coronary vessel quiescence at which time the vessels may be optimally

imaged/reconstructed (Liu et al. 2012, Wick et al. 2015b). Thus a comparison can be made between CT reconstructions from quiescent phases calculated using the IVS motion quantified from both B-mode echocardiography cine images and retrospective CTA reconstructions for a given patient. This comparison is made to assess the utility of echocardiography as an indicator of continuous-time cardiac quiescence.

Unfortunately, the ultimate goal of employing echocardiography to provide real-time, prospective gating information may be challenging since it requires the presence of an ultrasound transducer within the CT scanner. This transducer can cause streak artifacts in the CT images potentially rendering the CTA images non-diagnostic. One possible solution would be specifically designed ultrasound transducers with reduced beam-steering hardware. Another, more immediate, solution is to employ gating strategies based on CT-compatible modalities derived from the mechanics of the heart—seismocardiography (SCG) (Zanetti & Salerno 1991) or impedance cardiography (ICG) (Sherwood et al. 1990)—that can potentially be used for gating CTA. As a step toward validating these strategies, both SCG- or ICG-based gating can be evaluated by using echocardiography as a surrogate marker of cardiac motion. Specifically, if we can show that quiescent phases detected by echocardiography are able to provide diagnostically non-inferior coronary CT images compared to phases selected from retrospective CTA, then echocardiography could serve as a baseline to establish the relationship between salient signal features of these CT-compatible modalities and quiescent phases of the cardiac cycle. This use of echocardiography is appealing since echocardiography, unlike CTA, does not require ionizing radiation, allowing for significant experimentation with SCG and ICG for cardiac gating in a safe manner. Specifically, quiescent phases predicted using SCG or ICG can be compared to those detected from synchronously acquired B-mode echocardiography on a beat-by-beat basis. This will allow for the performance of real-time, CT-compatible gating strategies to be assessed, aiding in the development, refinement, and validation of these SCG- or ICG-based techniques.

The overarching goal of this work is to investigate echocardiography as an indication of cardiac quiescent phases. As a three-dimensional indication of cardiac quiescence, quiescent phases calculated from CTA are used as a baseline for comparison with two-dimensional B-mode echocardiography detected quiescent phases. This work employs existing techniques for quantifying cardiac motion from two-dimensional B-mode echocardiography and three-dimensional CT reconstructions to investigate the suitability of echocardiography as a continuous-time indication of cardiac quiescence. CT-detected quiescent phases are used as a baseline indication of cardiac quiescence. For this work, cardiac quiescent phases are calculated for 10 cardiac patients from contemporaneously obtained echocardiography and cardiac CT data. Motion profiles and quiescent phases are calculated using 1) a phase-to-phase deviation technique for CT (Wick et al. 2015b) and 2) a frame-to-frame deviation technique for echocardiography (Wick et al. 2013). In addition, the quiescent phases predicted internally by the CT machine are obtained. For each patient, the diagnostic quality of the coronary vessels from the CT reconstructions corresponding to these three phases was determined by a board-certified radiologist who is fellowship-trained in cardiothoracic radiology. The main objective is to provide a methodology to investigate the suitability of using quiescent phases identified by echocardiography as a proxy for those calculated from

CT. The cardiac motion of the IVS will be shown to be similar when calculated from echocardiography B-mode sequences and cardiac CT reconstructions for 10 patients. Additionally, the diagnostic quality of the CT reconstructions from these phases will be shown to be non-inferior, suggesting that B-mode echocardiography can be used as a tool for analyzing cardiac motion with respect to CTA and cardiac quiescence.

## 2. Methods

### 2.1. Data Acquisition

Ten cardiac patients, receiving retrospective cardiac CT exams unrelated to this study, were recruited for a supplemental echocardiography exam. Patients were not pre-treated to suppress heart rate. Approval for this study was granted by the Emory University Institutional Review Board.

Retrospective cardiac CT data were acquired using a Siemens Somatom Definition dual-source 64-slice CT scanner with a temporal resolution of 83 ms (Siemens, Erlangen, Germany). Cardiac patients were instructed to hold their breath during CT data acquisition. CT reconstructions were made from 0% to 98% at 2% increments based on the ECG signal used for gating during the exam, resulting in 50 reconstructed CT volumes per patient. Retrospective CT acquisition was necessary for this study so that cardiac motion could be quantified throughout the cardiac cycle, rather than at just one phase.

Two-dimensional B-mode echocardiography and ECG data were synchronously acquired using an Ultrasonix SonixTouch ultrasound machine (Analogic, Peabody, MA, USA). The echocardiography exams took place either shortly before or after the CT exams. Echocardiography and ECG data were recorded at rates of 50 frames-per-second and 200 Hz, respectively. Echocardiography B-mode sequences of the IVS were obtained from the apical four-chamber view. Patients were instructed to hold their breath during each of the multiple 10 second acquisitions, mimicking the instructions received during a CT exam.

### 2.2. Calculation of Quiescent Phases

Quiescent phases are calculated for each patient from both echocardiography and CT using correlation-based deviation methods (Wick et al. 2013, Wick et al. 2015b). The methods for calculating quiescence from echocardiography can be seen as an extension of the methods proposed by Tridandapani et al. (2005), however that work used one-dimensional M-mode data without evaluating corresponding patient CT data. An overview of the techniques used to quantify quiescence is provided below for convenience. Deviation is an inverse function of the correlation between frames and phases for echocardiography and CT, respectively, and has been shown to be linearly related to the velocity of the IVS (Wick et al. 2013). This relationship relies on sufficient contrast between the IVS and ventricles, minimal IVS deformation between neighboring frames/phases, and the shape of the IVS being somewhat circular/spherical. Discrepancies in the last requirement result in increased deviation sensitivity to motion in the direction of the minor axis of the IVS. In practice this has not been an issue and the accuracy of this approach has been verified using two-dimensional IVS tracking (Wick et al. 2013). Deviation,  $D(i, j)$ , is defined as

$$\mathbf{D}(\mathbf{i}, \mathbf{j}) = 1 - \rho_S(\mathbf{i}, \mathbf{j}), \quad (1)$$

where  $\rho_S(i, j)$  is the Pearson correlation coefficient between frames (for echocardiography) or phases (for CT)  $i$  and  $j$  over a static region of pixels or voxels  $S$ . Examples of these regions containing the IVS are shown in Fig. 1 for both echocardiography and CT. The IVS was observed because it is readily identifiable in echocardiography and fulfills the characteristics necessary for the deviation signal to approximate velocity magnitude. By calculating  $\mathbf{D}(i, j)$  for all  $i$  and  $j$ , a *deviation matrix* is formed that can be used to visualize cardiac quiescence. An example of such a deviation matrix for one cardiac cycle is given in Fig. 2, where blue regions along the diagonal correspond to low deviation and hence cardiac quiescence.

A *deviation signal* representing motion throughout the cardiac cycle is constructed from the values of the deviation matrix near the diagonal. The deviation signal,  $d(i)$ , represents the output of a moving averager sliding along the diagonal of  $\mathbf{D}(i, j)$  with a length corresponding to the acquisition time of the dual-source CT scanner used for this study, 83 ms. As a result,  $d(i)$  will represent the average amount of deviation—and hence motion—for a CT acquisition time interval centered at  $i$ . Specifically, the deviation signal is defined as

$$d(i) = \frac{1}{N^2} \sum_{n_1=-N/2}^{N/2} \sum_{n_2=-N/2}^{N/2} \mathbf{D}(\mathbf{i} + \mathbf{n}_1, \mathbf{i} + \mathbf{n}_2), \quad (2)$$

where  $N$  is the number of frames or phases corresponding to 83 ms.<sup>‡</sup> Quiescent phases are identified as the phase of minimum deviation for a given deviation signal. These quiescent phases are labeled as  $P_{CT}$  and  $P_{echo}$  for the phases identified from CT and echocardiography data, respectively. Examples of the deviation signal from both CT and echocardiography are given in Fig. 3.

The differences between the methods for calculating  $\mathbf{D}(i, j)$  and  $d(i)$  for echocardiography and CT are few. Specifically,  $i$  and  $j$  represent indices of frames for B-mode echocardiography and phases (%) for cardiac CT reconstructions. The static set  $S$ , over which the frames and phases are compared, differs between echocardiography and CT. For echocardiography,  $S$  is the set of pixels inside a two-dimensional rectangle containing the IVS in all frames. This region was selected manually to contain the IVS throughout the cardiac cycle by observing IVS motion during the initial two seconds of each B-mode sequence. For CT,  $S$  is the smallest set of three-dimensional voxels containing the IVS for all phases. For details on the construction of  $S$  for CT please refer to Wick et al. (2015b). Lastly, because echocardiography is a real-time method, multiple cardiac cycles of the deviation signal are obtained as opposed to just one composite cycle for CT. The multiple cycles of data are segmented by the R-peak of the ECG. A singular deviation signal is

<sup>‡</sup>Because  $\mathbf{D}(i, j)$  is symmetric, Eq. 2 can be calculated more efficiently than presented, however, it is given as above for increased interpretability.

constructed for echocardiography data by time-scaling and averaging all cycles of the deviation signal data within  $\pm 1$  beat per minute (bpm) of the average heart rate observed during each patient's CT exam. This choice is made to facilitate the comparison between the echocardiography and CT deviation signals at the same heart rate.

In addition to the quiescent phases detected from the deviation of the CT and echocardiography data, the quiescent phases predicted internally by the CT scanner for each subject using the proprietary BestPhase algorithm (Siemens, Erlangen, Germany) were recorded as  $P_{BP}$  (Seifarth et al. 2009). The BestPhase algorithm calculates quiescence from retrospective CT based on a motion estimate derived from low-resolution CT reconstructions of the whole heart. It is important to note that unlike the retrospective CT reconstructions used for this work, standard prospective gating is done solely based on the heart rate and ECG signal.

### 2.3. Diagnostic Quality of Quiescent Phases

The diagnostic quality of the CT reconstructions corresponding to quiescent phases calculated using three different methods was obtained. These phases include those calculated using the methods of 2.2 ( $P_{CT}$ ,  $P_{echo}$ ) in addition to those calculated directly from the CT scanner using the proprietary CT-data-based BestPhase algorithm ( $P_{BP}$ ). It should be noted that the goal is not a direct comparison between the proposed echocardiography- and CT-based retrospective methods and ECG-based prospective methods; rather that there is room for improvement for prospective gating methods and that echocardiography can be used to develop these new and improved methods.

The order of the 30 reconstructions—three phase calculation methods per patient, 10 cardiac patients—was randomized prior to the reconstructions being interpreted by a board-certified, fellowship-trained, cardiothoracic radiologist with five years experience in clinical practice after training. The diagnostic quality of the left main (LM), left anterior descending (LAD), left circumflex (LCX), and right coronary artery (RCA) was graded on a four-point Likert response format for each quiescent phase. The grade levels are defined as follows: 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.

## 3. Results

Echocardiographic B-mode sequences and retrospective cardiac CT reconstructions were obtained for 10 cardiac patients. From this data, echocardiography- and CT-based deviation signals were computed for each subject. Examples of these deviation signals are shown in Fig. 3 for two patients.

The most quiescent phases as determined from the minima of the echocardiography and CT deviation signals as described in 2.2 were calculated. In addition, the quiescent phase predicted internally by the CT scanner were obtained. The quiescent phases for all patients are given in Table 1 and indicate a general agreement between the methods, with a mean



correlation of 0.956 between the methods. Note that the quiescent phases transition from diastole to systole as heart rate increases, agreeing with the accepted standard that at high heart rates CT data should be acquired during systole (Desjardins & Kazerooni 2004). A graphical representation of the data in Table 1 is provided in Fig. 4. Of note is that the most quiescent phase occurs in systole at higher heart rates as shown for Patients 8, 9, and 10. This is because the systolic phase does not decrease with heart rate as much as the diastolic phase and agrees with the generally accepted conclusion that beyond 70–80 bpm that triggering should occur in systole (Lu et al. 2001, Husmann et al. 2007).

The diagnostic qualities of the CT reconstructions for the echocardiography- and CT-selected quiescent phases were found to be comparable by the cardiothoracic radiologist who was blinded to the source from which the quiescent phases were derived. A summary of the diagnostic quality grades are provided in Table 2 along with the  $p$ -values from the Wilcoxon signed-rank test.<sup>§</sup> Though the large  $p$ -values of Table 2 do not guarantee the null hypothesis (median difference of zero), they do suggest that, at least for these patients, there is no significant difference in the diagnostic quality between echocardiography- and CT-based quiescent phase selection. This suggests that echocardiography can be used to investigate cardiac quiescence in the context of CTA, avoiding radiation and allowing for real-time analysis of quiescence. Also of note, is that at low heart rates, the length of the diastolic quiescent phase is generally much longer than the amount of time needed for CT reconstruction. As a result the sensitivity to mistiming decreases as heart rate decreases. Conversely, as heart rate increases gating accuracy becomes increasingly important. Lastly, the diagnostic quality of the LM and LAD was consistently superior to that of the LCX and RCA. This is due to the LCX and RCA exhibiting larger velocities throughout the cardiac cycle (Husmann et al. 2007).

CT reconstructions of Patient 8 with a heart rate of 83 bpm are provided in Fig. 5. This patient is unique in that  $P_{echo}$  occurred in diastole and  $P_{CT}$  occurred in systole. This is potentially because 83 bpm is in the range of heart rates where the optimal quiescent phase transitions to systole. Of note, the diagnostic image quality of both phases is comparable, even though the reconstructions are from different periods of the cardiac cycle. This suggests that echocardiography can identify quiescent phases even when they are not similar to those of CT. If restricted to systole,  $P_{echo}$  remains 40% and  $P_{CT}$  becomes 42% for this patient, further suggesting echocardiography as an indicator of cardiac quiescence. For this reason, the quiescent phases of Patient 8 were omitted from the correlation calculation above.

## 4. Discussion

A method for comparing the quiescent phases and cardiac motion calculated from echocardiography (Wick et al. 2013) to those calculated from CT (Wick et al. 2015b) was developed. CT-detected quiescent phases were used as a baseline indication of cardiac quiescence to investigate echocardiography as an indication of these phases. The results of this work suggest that echocardiography can be used to investigate cardiac motion in the context of CTA, i.e., quiescence calculated from echocardiography can be used as a proxy

<sup>§</sup>Two-sided  $p$ -values are calculated by doubling the largest one-sided value and are capped at 1.0.

for cardiac quiescence. This utility of echocardiography is important because it allows for quiescence to be observed on a beat-by-beat basis without ionizing radiation. Echocardiography can then be used as a tool to develop CT-compatible gating techniques for CTA based on cardiac motion as opposed to gating solely based on the ECG.

The ECG, as a measure of the instantaneous electrical state of the heart, is a suboptimal indicator of the instantaneous mechanical state of the heart. Inter- and intra-subject variability has been shown between electrical and mechanical events of the heart (Wick et al. 2012), indicating that variability between the ECG and quiescent phases also exists. Achenbach et al. (2012) showed that at high heart rates diagnostic images could be obtained for 95% of patients but that the reconstruction phase varied from 25% to 75%. Therefore, to reliably obtain diagnostic quality images, CT acquisition must occur continuously throughout this interval of the cardiac cycle. With more accurate, personalized identification of the optimal quiescent phase, this interval could be dramatically shortened resulting in a significant reduction in patient radiation exposure.

ECG-based phases were not compared to the phases identified in this work. The performance of new CT-compatible gating methods, i.e., SCG and ICG, relative to standard ECG-based prospective gating is a topic for future work with a much larger number of patients, especially those with higher heart rates. In addition, it is difficult to specify ECG-based phases because there is not a consistent method used to determine these phases. Methods in clinical use are generally proprietary and vary between CT manufacturers. As a further example of this inconsistency, three different, well-cited references from the literature recommend different phases for the same heart rate ranges (Husmann et al. 2007, Seifarth et al. 2009, Srichai et al. 2009).

Based on the results of this work, echocardiography can be used to develop new methods for gating CTA based on cardiac motion. For example, the seismocardiogram (SCG) (Zanetti & Salerno 1991) is a measure of chest wall acceleration caused by cardiac motion from which quiescent phases can be identified (Wick et al. 2015a). Another cardiac-motion based modality that could potentially be used for CTA gating is impedance cardiography (ICG) (Sherwood et al. 1990). ICG measures the variance in the impedance of the chest as a result of cardiac activity and has been shown to have features that strongly correspond to mechanical states of the heart. Lastly, continuous wave radar embedded in the CT table has been suggested as a potential modality for CTA gating (Pfanner et al. 2014). Because these CT-compatible modalities are indications of cardiac motion, they may more reliably predict cardiac quiescence than the current standard ECG. Echocardiography can serve as a baseline to establish the relationship between salient signal features of these modalities and quiescent phases of the cardiac cycle. In addition to being indications of mechanical cardiac activity, these modalities also contain salient signal features closer in temporal proximity to desired quiescent phases than the ECG. As shown in the Appendix, gating performance increases linearly as the relative temporal distance between cardiac features and quiescent phases decreases. This is especially important for patients with high heart rate variability or arrhythmias. It should be noted that this improvement cannot be demonstrated without simulating a prediction framework, which is a topic for future work.



This work has shown that there is no significant difference in the diagnostic quality of the coronary vessels between phases retrospectively-calculated from echocardiography and CT for the 10 patients included in this study. This suggests that B-mode echocardiography can be used as a surrogate marker of cardiac quiescence and thus serve as a useful tool to validate other CT-compatible gating methods in the early stages of development.

#### 4.1. Limitations

The primary limitation of this study is that only 10 patients were included. This work is primarily intended to present a methodology for obtaining and comparing CT reconstructions from echocardiography- and CT-selected quiescent phases. Expanding on these initial results by including more patients is a topic for future research. Additionally, a larger patient population would allow for more powerful conclusions regarding diagnostic quality with respect to cardiac phase and heart rate to be made. For instance, additional patients with heart rates near the rate when optimal quiescence transitions from mid-diastole to end-systole would allow for a better understanding of this important bifurcation point in the gating decision process.

An additional limitation is that the CT and echocardiography data were obtained contemporaneously and not simultaneously. Thus there may be some heart rate variation between when the CT was obtained and when the echocardiography was obtained.

#### 4.2. Conclusion

Methods to validate the use of B-mode echocardiography as a predictor of cardiac quiescence for CTA were presented in this work. The results suggest that cardiac motion calculated from echocardiography can be used as a baseline to analyze new CT-compatible gating techniques in real-time on a beat-by-beat basis in an inexpensive manner without ionizing radiation, unlike CT. Such emerging gating techniques include the use of SCG (Wick et al. 2015a), ICG (Sherwood et al. 1990), and continuous wave radar (Pfanner et al. 2014). Echocardiography can serve as a bridge between CT and these modalities. The development of these gating methods could lead to wider use of prospectively-gated CTA with improved diagnostic quality, fewer complications, and less radiation dose than both retrospective CTA and the standard CCA exam.

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### Appendix

It is important to understand the benefit of performing cardiac gating using signals with features close in temporal proximity to the desired quiescent phases. Given that it is impossible to know the true duration of a cardiac cycle prior to gating within that cycle, an estimate of this length must be calculated. This is usually done based on the lengths of some number of preceding cycles. For patients with large amounts of heart rate variability this

prediction is inherently error-prone. An example of this difficulty is shown for the ECG in Fig. A1. For these cases especially, it is important to understand that *cardiac phase prediction error decreases linearly as the relative temporal distance between the cardiac signal (e.g., the ECG, SCG, or ICG) feature and the desired quiescent phase decreases*. A short mathematical justification is given below.

Let  $T$  be the true duration of a given cardiac cycle in seconds and  $P$  be the fraction of that cycle indicating the timing of the desired quiescent phase from the triggering feature. Then, the time delay  $\tau$  in seconds between the triggering feature and the quiescent phase can be expressed as

$$\tau = P \cdot T \quad P \in (0, 1). \quad (\text{A.1})$$

Note that instantaneous heart rate  $r$  and cycle length  $T$  are deterministically related by  $r = 60 \cdot T^{-1}$ . Now, let  $\hat{\tau}$  be the predicted delay to the cardiac quiescent phase,  $\hat{T}$  be the estimated cycle length,  $e_T$  be the error off  $\hat{T}$ , and  $e_\tau$  be the resulting error of  $\hat{\tau}$ . Then,  $\hat{\tau}$  can be expressed as

$$\hat{\tau} = P \cdot \hat{T} \quad (\text{A.2})$$

$$= P \cdot (T + e_T) \quad (\text{A.3})$$

$$= P \cdot T + P \cdot e_T \quad (\text{A.4})$$

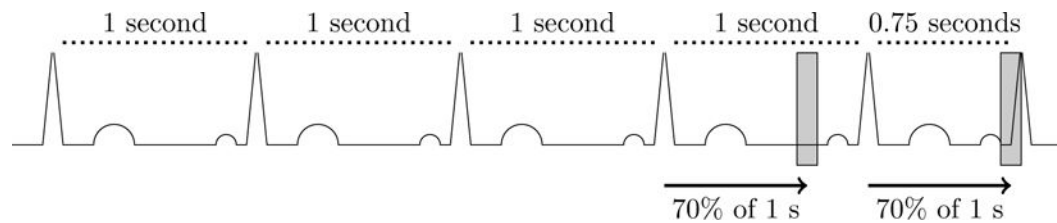
$$= \tau + P \cdot e_T \quad (\text{A.5})$$

$$= \tau + e_\tau. \quad (\text{A.6})$$

Therefore,

$$e_\tau = P \cdot e_T \quad (\text{A.7})$$

and  $e_\tau$  will decrease linearly with  $P$  for a given  $e_T$ . As a result, gating performance will increase linearly with a relative decrease in the time between quiescent phases and cardiac signal features used to trigger CT acquisition.



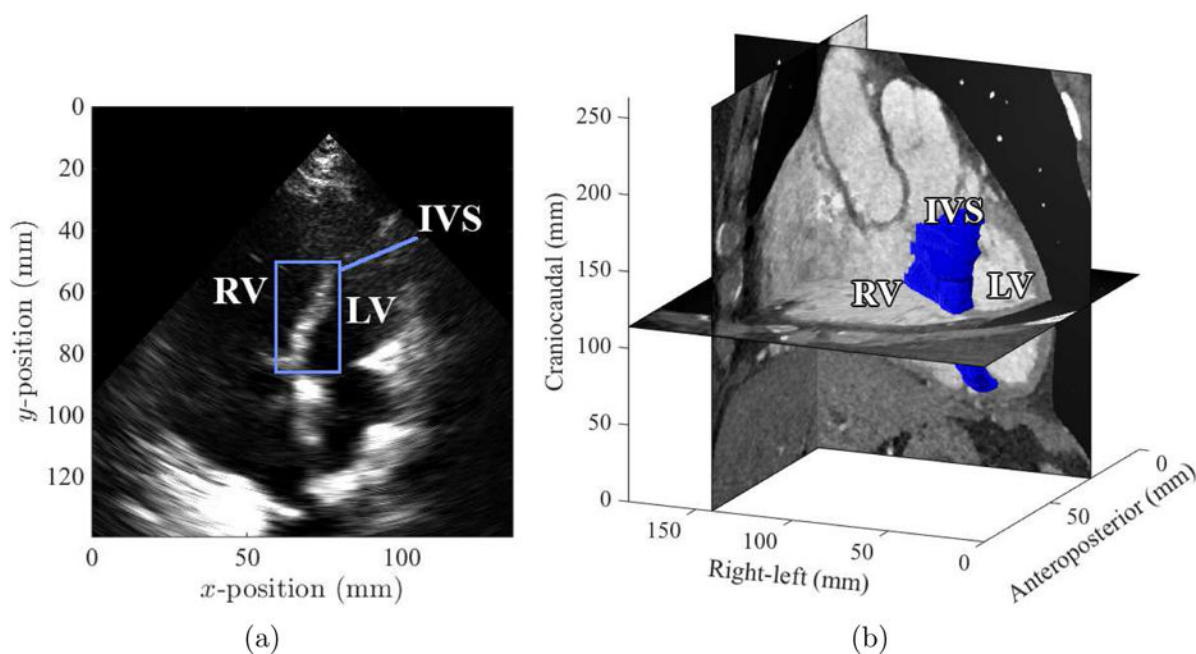
**Figure A1.**

Example of real-time prospective ECG-based gating and the difficulties associated with heart rate variability. Grey bars indicate CT acquisition delayed from the previous ECG R-peak by 70% of the predicted cardiac cycle length. The predicted cycle length is estimated from the R-R intervals of the preceding cycles. For the last cycle, this results in severely mistimed CT acquisition due to heart rate variability.

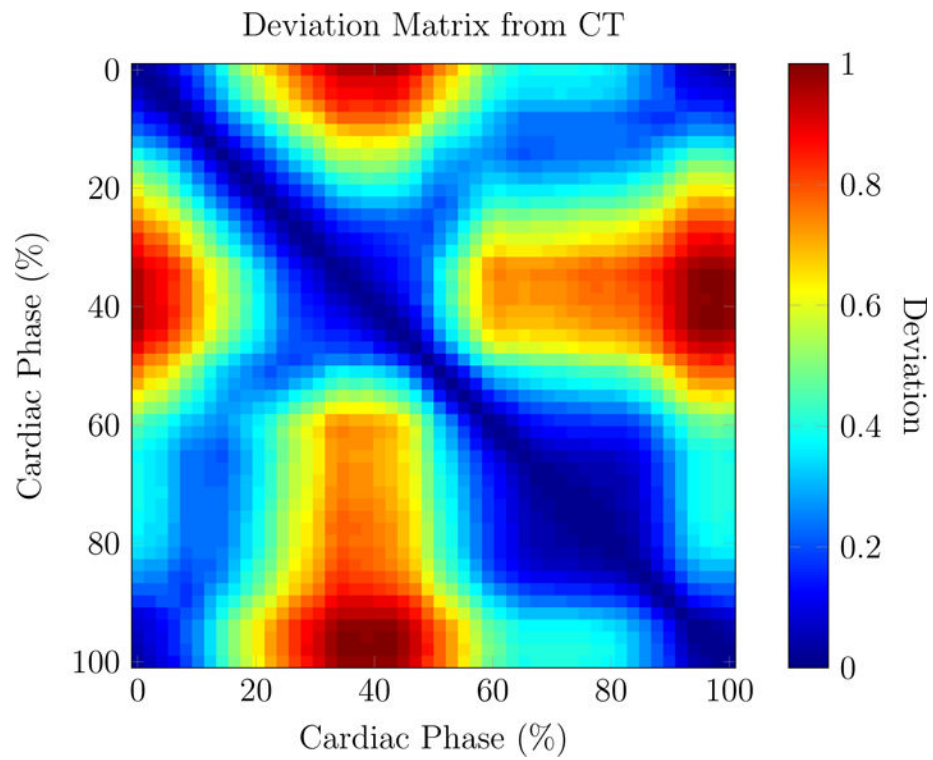
## References

- Achenbach S, Manolopoulos M, Schuhbäck A, Ropers D, Rixe J, Schneider C, Krombach GA, Uder M, Hamm C, Daniel WG, Lell M. Influence of heart rate and phase of the cardiac cycle on the occurrence of motion artifact in dual-source CT angiography of the coronary arteries. *J Cardiovasc Comput Tomogr*. 2012; 6(2):91–98. [PubMed: 22381662]
- Applegate RJ, Sacrinty MT, Kutcher MA, Kahl FR, Gandhi SK, Santos RM, Little WC. Trends in vascular complications after diagnostic cardiac catheterization and percutaneous coronary intervention via the femoral artery, 1998 to 2007. *JACC Cardiovasc Interv*. 2008; 1(3):317–326. [PubMed: 19463320]
- Desjardins B, Kazerooni EA. ECG-gated cardiac CT. *AJR Am J Roentgenol*. 2004; 182(4):993–1010. [PubMed: 15039178]
- Husmann L, Leschka S, Desbiolles L, Schepis T, Gaemperli O, Seifert B, Cattin P, Frauenfelder T, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H. Coronary artery motion and cardiac phases: dependency on heart rate – implications for CT image reconstruction. *Radiology*. 2007; 245(2):567–576. [PubMed: 17848683]
- Liu G, Qi XL, Robert N, Dick AJ, Wright GA. Ultrasound-guided identification of cardiac imaging windows. *Medical Physics*. 2012; 39(6):3009–3018. [PubMed: 22755685]
- Lu B, Mao SS, Zhuang N, Bakhsheshi H, Yamamoto H, Takasu J, Liu SC, Budoff MJ. Coronary artery motion during the cardiac cycle and optimal ECG triggering for coronary artery imaging. *Invest Radiol*. 2001; 36(5):250–256. [PubMed: 11323512]
- Menke J, Unterberg-Buchwald C, Staab W, Sohns JM, Seif Amir Hosseini A, Schwarz A. Head-to-head comparison of prospectively triggered vs retrospectively gated coronary computed tomography angiography: Meta-analysis of diagnostic accuracy, image quality, and radiation dose. *American Heart Journal*. 2013; 165(2):154–63.e3. [PubMed: 23351817]
- Patel MR, Peterson ED, Dai D, Brennan JM, Redberg RF, Anderson HV, Brindis RG, Douglas PS. Low diagnostic yield of elective coronary angiography. *N Engl J Med*. 2010; 362(10):886–895. [PubMed: 20220183]
- Pfanner F, Allmendinger T, Bohn B, Flohr T, Kachelrieß M. Monitoring cardiac motion in CT using a continuous wave radar embedded in the patient table. *Medical Physics*. 2014; 41(8):081908. [PubMed: 25086539]
- Roger VL, Go AS, Lloyd-Jones DM, Benjamin EJ, Berry JD, Borden WB, Bravata DM, Dai S, Ford ES, Fox CS, Fullerton HJ, Gillespie C, Hailpern SM, Heit JA, Howard VJ, Kissela BM, Kittner SJ, Lackland DT, Lichtman JH, Lisabeth LD, Makuc DM, Marcus GM, Marelli A, Matchar DB, Moy CS, Mozaffarian D, Mussolino ME, Nichol G, Paynter NP, Soliman EZ, Sorlie PD, Sotoodehnia N, Turan TN, Virani SS, Wong ND, Woo D, Turner MB, American Heart Association Statistics Committee and Stroke Statistics Subcommittee. Heart disease and stroke statistics–2012 update: A report from the American Heart Association. *Circulation*. 2012; 125(1):e2–e220. [PubMed: 22179539]

- Seifarth H, Puesken M, Wienbeck S, Maintz D, Fischbach R, Heindel W, Juergens KU. Automatic selection of optimal systolic and diastolic reconstruction windows for dual-source CT coronary angiography. *Eur Radiol.* 2009; 19(7):1645–1652. [PubMed: 19238394]
- Sherwood A, Allen MT, Fahrenberg J, Kelsey RM, Lovallo WR, Doornen LJP. Methodological guidelines for impedance cardiography. *Psychophysiology.* 1990; 27(1):1–23. [PubMed: 2187214]
- Srichai MB, Hecht EM, Kim D, Babb J, Bod J, Jacobs JE. Dual-source computed tomography angiography image quality in patients with fast heart rates. *J Cardiovasc Comput Tomogr.* 2009; 3(5):300–309. [PubMed: 19643693]
- Tridandapani S, Fowlkes JB, Rubin JM. Echocardiography-based selection of quiescent heart phases: Implications for cardiac imaging. *Journal of Ultrasound in Medicine.* 2005; 24(11):1519–1526. [PubMed: 16239655]
- Vembar M, Garcia MJ, Heuscher DJ, Haberl R, Matthews D, Böhme GE, Greenberg NL. A dynamic approach to identifying desired physiological phases for cardiac imaging using multislice spiral CT. *Medical Physics.* 2003; 30(7):1683. [PubMed: 12906185]
- Wick CA, Inan OT, McClellan JH, Tridandapani S. Seismocardiography-Based Detection of Cardiac Quiescence. *IEEE Trans Biomed Eng.* 2015a; 62(8):2025–2032. [PubMed: 25769145]
- Wick CA, McClellan JH, Arepalli CD, Auffermann WF, Henry TS, Khosa F, Coy AM, Tridandapani S. Characterization of cardiac quiescence from retrospective cardiac computed tomography using a correlation-based phase-to-phase deviation measure. *Medical Physics.* 2015b; 42(2):983–993. [PubMed: 25652511]
- Wick CA, McClellan JH, Ravichandran L, Tridandapani S. Detection of cardiac quiescence from B-mode echocardiography using a correlation-based frame-to-frame deviation measure. *IEEE Journal of Translational Engineering in Health and Medicine.* 2013; 1:1–11.
- Wick CA, Su JJ, McClellan JH, Brand O, Bhatti PT, Buice AL, Stillman AE, Tang X, Tridandapani S. A system for seismocardiography-based identification of quiescent heart phases: Implications for cardiac imaging. *IEEE Transactions on Information Technology in Biomedicine.* 2012; 16(5):869–877. [PubMed: 22581141]
- Zanetti JM, Salerno DM. Seismocardiography: a technique for recording precordial acceleration. *Computer-Based Medical Systems, 1991, Proceedings of the Fourth Annual IEEE Symposium.* 1991:4–9.

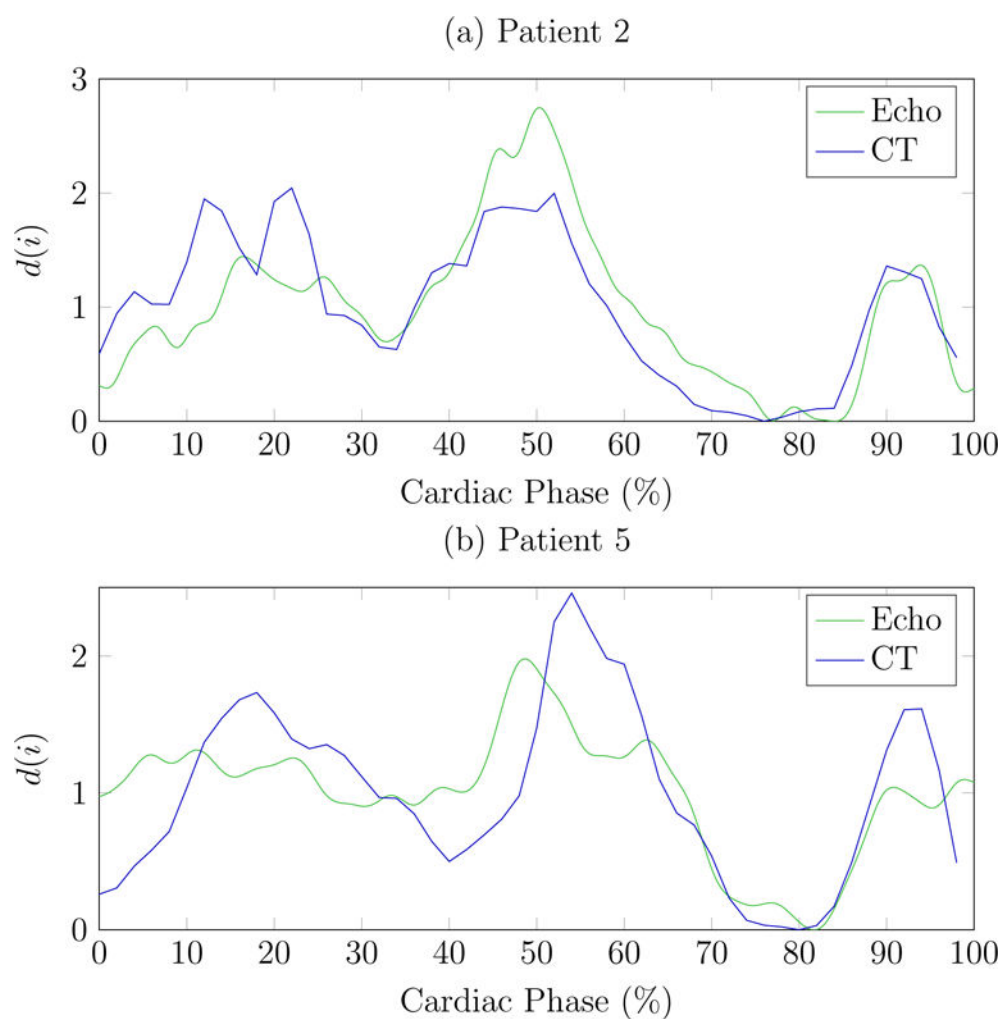


**Figure 1.**  
Location of the IVS for (a) echocardiography and (b) CT. For CT, the blue volume corresponds to the IVS, segmented using the techniques presented by Wick et al. (2015b).

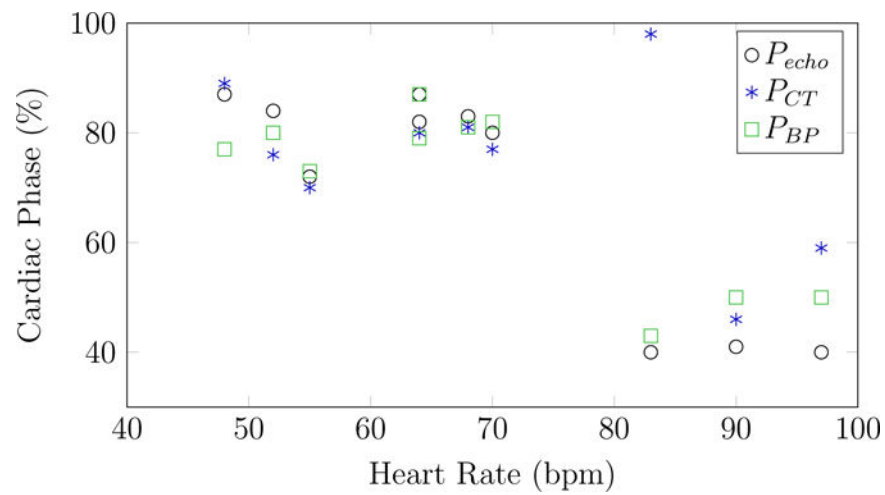


**Figure 2.** Deviation matrix of the IVS for Patient 5 calculated from CT representing one cardiac cycle. Quiescent regions of the cardiac cycle can be rapidly interpreted as blue regions that correspond to low deviation. In addition, the deviation matrix allows for the similarity between different phases of the cardiac cycle to be quickly observed.



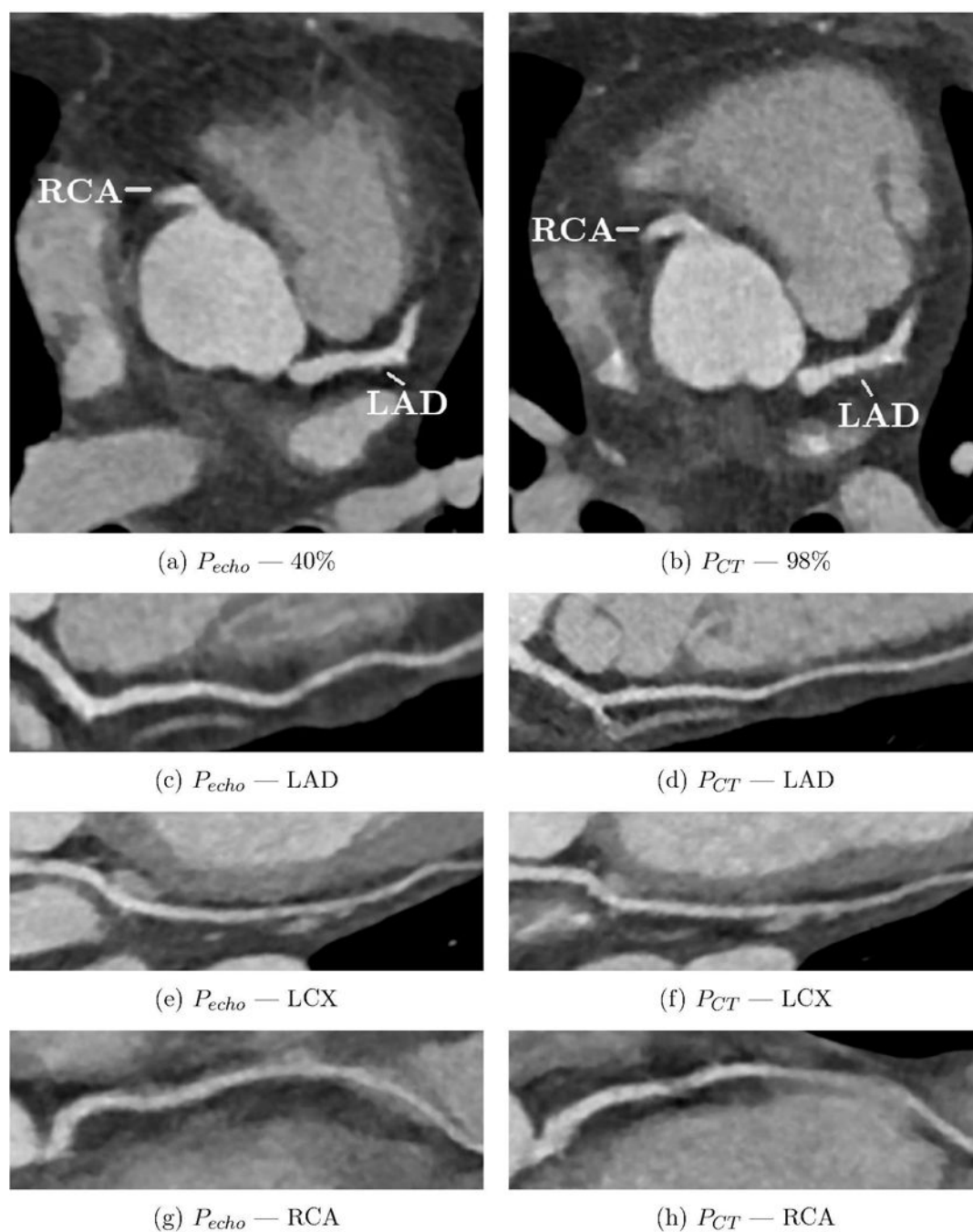


**Figure 3.** Deviation signals of the IVS from echocardiography and CT for Patient 2 and Patient 5.



**Figure 4.**

Quiescent phases of 10 cardiac patients.  $P_{echo}$  and  $P_{CT}$  are the quiescent phases calculated from echocardiography- and CT-based deviation methods, whereas  $P_{BP}$  is the quiescent phase predicted by the CT scanner using the proprietary BestPhase algorithm.



**Figure 5.**

CT reconstructions of Patient 8 with a heart rate of 83 bpm. Two phases are shown:  $P_{echo}$  of 40% calculated from echocardiography (left) and  $P_{CT}$  of 98% calculated from CT (right). Curved planar reconstructions are shown for the LAD (c,d), LCX (e,f), and RCA (g,h). With the exception of the distal portion of the RCA being worse for  $P_{CT}$ , the diagnostic image quality of both phases is comparable.

**Table 1**

Quiescent phases detected from echocardiography and CT.

Patient <sup>*</sup>	Heart Rate	$P_{echo}$	$P_{CT}$	$P_{BP}$
1	48 bpm	87 %	89 %	77 %
2	52 bpm	84 %	76 %	80 %
3	55 bpm	72 %	70 %	73 %
4	64 bpm	87 %	80 %	87 %
5	64 bpm	82 %	80 %	79 %
6	68 bpm	83 %	81 %	81 %
7	70 bpm	80 %	77 %	82 %
8	83 bpm	40 %	98 %	43 %
9	90 bpm	41 %	46 %	50 %
10	97 bpm	40 %	59 %	50 %

\* Patients have been sorted by heart rate in ascending order.

**Table 2**

Mean Diagnostic Quality Grades for Each Coronary Vessel.

	$P_{echo}$	$P_{CT}$ (p-value)	$P_{BF}$ (p-value)
LM	1.5 ±0.53	1.5 ±0.71 (1.00)	1.6 ±0.70 (1.00)
LAD	2.4 ±0.97	2.4 ±0.82 (1.00)	2.3 ±0.95 (1.00)
LCX	2.5 ±1.18	2.5 ±0.97 (1.00)	2.7 ±0.95 (0.69)
RCA	3.0 ±0.82	3.0 ±0.94 (1.00)	2.8 ±0.79 (0.57)
Mean	2.35±0.61	2.33±0.60 (0.91)	2.35±0.65 (0.98)

Grade: 1 = excellent, 2 = good, 3 = adequate, 4 = nondiagnostic. p-values taken against  $P_{echo}$ .