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Novel phase-based noise reduction strategy for quantification of left ventricular function and mass assessment by cardiac CT: Comparison with cardiac magnetic resonance

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Abstract

Background—Tube current modulation in retrospective ECG gated cardiac computed tomography (CT) results in increased image noise and may reduce the accuracy of left ventricular (LV) ejection fraction (EF) and mass assessment.

Objective—To examine the effects of a novel CT phase-based noise reduction (NR) algorithm on LV EF and mass quantification as compared to cardiac magnetic resonance (CMR).

Methods—In 40 subjects, we compared the LV EF and mass between CT and CMR. In a subset of 24 subjects with tube current modulated CT, the effect of phase-based noise reduction strategies on contrast-to-noise ratio (CNR) and the assessment of LV EF and mass was compared to CMR.

Results—There was excellent correlation between CT and CMR for EF ($r = 0.94$) and mass ($r = 0.97$). As compared to CMR, the limits of agreement improved with increasing strength of NR strategy. There was a systematic underestimation of LV mass by CT compared to CMR with no NR (-10.3 ± 10.1 g) and low NR (-10.3 ± 12.5 g), but was attenuated with high NR (-0.5 ± 8.3 g). Studies without NR had lower CNR compared to low and high NR at both the ES phase and ED phase (all $p < 0.01$).

Conclusions—A high NR strategy on tube current modulated functional cardiac CT improves correlation of EF compared to CMR and reduces variability of EF and mass evaluation by increasing the CNR. In an effort to reduce radiation dose with tube current modulation, this strategy provides better image quality when LV function and mass quantification is needed.

Keywords

Left ventricular function; Left ventricular mass; Noise reduction; Computed tomography

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Conflict of interest

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1. Background

Left ventricular (LV) ejection fraction (EF) and mass provide both diagnostic and prognostic information for various cardiac diseases [1–6]. Advanced non-invasive imaging modalities such as computed tomography (CT) and cardiac magnetic resonance (CMR) can be used to assess LV EF and mass without relying on geometric assumptions or adequate acoustic windows. CMR assessment of LV EF and mass has been found to be highly reproducible and this modality is thus considered the reference standard for measurement of these parameters [7,8]. However, with improvements in CT technology, retrospectively-gated cardiac CT has been utilized as an alternative imaging modality for the assessment of LV EF or mass [9]. These studies are performed particularly when there are contraindications for CMR, when echocardiographic image quality is suboptimal or when CT imaging is performed for other indications such as for detection of coronary artery disease [10].

Despite the advantages of CT, exposure to radiation remains a concern [11], and strategies to reduce radiation dose while maintaining accuracy and reproducibility of LV EF and mass measurements are essential. Tube current modulation applied to retrospectively-gated CT studies reduces radiation dose, at the expense of increased image noise [12]. Noise reduction strategies have the potential to improve image quality and hence may impact the accuracy and reproducibility of LV EF and mass measurements. One method of image noise reduction involves using deformable registration, where voxels in each phase of a retrospectively-gated CT functional data set are aligned based on anatomy that is consistently present through adjacent phases and interphase noise reduction filtering algorithms applied. We aim to investigate the correlation between CT and CMR assessment of LV EF and mass. We also aim to examine the effects of a novel phase-based noise reduction strategy on tube current modulated CT dataset for assessment of LV EF and mass compared to CMR and its effect on CT image noise.

2. Methods

2.1. Study populations

We performed LV EF and mass assessment in 40 patients referred to our institution for cardiac CT angiography to investigate for suspected coronary artery disease. All patients had CT imaging performed with retrospective ECG gating and also underwent CMR within 7 days of cardiac CT. LV EF and mass assessed by CMR was used as the standard reference. A subgroup of 24 patients who received tube current modulated CT were used to test the effect of various noise reduction strategies. The local Institutional Review Board approved the study protocol.

2.2. Cardiac computed tomography

2.2.1. CT imaging protocol—The cardiac CT examinations were performed on either a 64-slice single-source multi-detector CT scanner (Siemens Sensation 64, gantry rotation 330 ms, 32×0.6 mm collimation), 64-slice Dual Source CT scanner (Siemens Definition 64, gantry rotation time of 330 ms, $2 \times 64 \times 0.6$ mm collimation), or 128-slice Dual Source CT (Siemens Definition Flash, Siemens Healthcare, Forchheim, Germany, gantry rotation time of 280 ms, $2 \times 128 \times 0.6$ mm collimation). Tube potential was determined by body mass index (BMI) where 120 kV was used for those with BMI ≥ 25 kg/m² and 100 kV for patients with BMI < 25 kg/m². All CT examinations were performed with retrospective ECG gating ($n = 40$) and tube current modulation as clinically dictated ($n = 24$). ECG tube modulation was performed with 96% reduction ($n = 5$, 21%) and 80% reduction ($n = 19$, 79%) during systole. There was full radiation output during diastole, of which the duration expressed as percent of the R–R interval was variable, depending on the heart rate. The scanning delay

was determined using test bolus technique, followed by a contrast-enhanced CT scan with a flow rate of 5–6 mL/sec of an iodinated contrast agent (Iopamidol 370 (Isovue), Bracco Diagnostics Inc., Princeton, NJ, USA) followed by 40 mL of saline flush. The 3D datasets were reconstructed every 5 or 10% of the R–R interval at a slice thickness of 1.5 mm with a reconstruction increment of 1.5 mm. The effective dose was calculated by multiplying the dose-length product value by the effective dose coefficient of 0.014.

2.2.2. CT LV ejection fraction and mass—The cardiac CT functional series were transferred to an offline workstation (Ziostation, Qi Imaging, Redwood City, CA), where the LV EF and mass analysis were performed. A series of short axis slices of the LV were created from 2 orthogonal long axis views. The end systolic (ES) phase was defined as the phase with the smallest LV cavity and the end diastolic (ED) phase was defined as the phase with the largest LV cavity. Semi-automated epicardial and endocardial contours were adjusted at the LV ES and LV ED phases. Papillary muscles were excluded from the LV mass assessment and included in the LV cavity assessment. Simpson's rule was used to obtain the LV ES and LV ED volumes as well as for calculation of LV EF.

2.2.3. Noise reduction strategies—Noise reduction algorithm (PhyZiodynamic, Qi Imaging Redwood City, CA) was applied to the tube current modulated cardiac CT datasets ($n = 24$). The following strategies were applied to the CT dataset; (1) no noise reduction, (2) low noise reduction where 50% of the CT data were obtained from 2 neighboring phase and (3) high noise reduction where 70% of the CT data were obtained from 4 neighboring phases (Fig. 1 and Fig. 2).

2.2.4. Contrast to noise ratio—The contrast to noise ratio (CNR) was measured by placing a region of interest of 5 cm² in the LV cavity and one of 0.5 cm² in the myocardium at both the ES and ED phases. CNR is defined as the difference in mean Hounsfield unit (HU) between the LV cavity and myocardium, divided by the standard deviation of the LV cavity HU [13].

2.3. Cardiac magnetic resonance

2.3.1. CMR imaging protocol—All CMR studies were performed on a 1.5 Tesla MR scanner (Signa HDx, GE Healthcare, Milwaukee, WI). LV function was obtained with cine images using a balanced steady-state free precession (b-SSFP) technique. The scans were performed at a matrix of 192 × 192 with a slice thickness of 8 mm with no gap between slices. Short axis slices were obtained through the LV.

2.3.2. CMR LV ejection fraction and mass—For CMR, a series of short axis slices cine images were transferred to an offline workstation (CMR42, Circle Cardiovascular Imaging, Calgary) where the LV EF and mass analysis were performed. Similar to the CT analysis, the ES phase was defined as the phase with the smallest LV cavity and the ED phase was defined as the phase with the largest LV cavity. Epicardial and endocardial contours were adjusted at the LV ES and LV ED phases and Simpson's rule was used to obtain the LV ES and LV ED volumes as well as for calculation of LV EF. Similarly, the papillary muscles were excluded from the LV mass assessment and included in the LV cavity assessment.

2.4. Statistical analysis

Continuous variable are presented as mean ± standard deviation or median [25th, 75th interquartile range] as appropriate and categorical variables are presented as n (%). We used a Student's t -test to compare differences between two groups. To determine the correlation between groups, we used Pearson's correlation. Systematic error and the degree of

agreement for LV EF and mass as assessed by various noise reduction strategies on cardiac CT compared to CMR were assessed with Bland Altman's analysis. For reproducibility assessment, two cardiac CT readers performed measurements on the same 30 CT datasets from 10 randomly selected patients independently, with one reader performing the measurements twice one month later. We used intraclass correlation coefficient (ICC) for intra-observer and inter-observer agreement and paired *t*-test for determining the significance of the mean absolute differences. We used paired *t*-test to compare the differences in CNR between noise reduction strategies by CT and CMR. A 2-sided *p* value < 0.05 was considered to indicate statistical significance for all tests. Statistical analysis was performed with SPSS 17.0 (SPSS Inc., Chicago, Illinois).

3. Results

Table 1 summarizes the characteristics of the 40 patients who had both CT and CMR for analysis and the subgroup of 24 patients who had ECG-tube modulated CT scans. The CT radiation dose was lower in scans performed with tube current modulation compared to no tube current modulation (10.0 ± 4.9 mSv vs 14.4 ± 2.7 mSv, $P = 0.003$). However this was at the expense of lower CNR during both ES (8.3 ± 4.2 vs 11.6 ± 4.3 , $P = 0.02$) and ED phases (6.2 ± 3.7 vs 12.6 ± 15.6 , $p < 0.001$).

3.1. Correlation between CT and CMR

The median time between CT and CMR scans was 1.0 [1.0, 3.0] days. There was excellent correlation between CT and CMR for LV ES volume ($r = 0.98$) and LV ED volume ($r = 0.96$, both $p < 0.001$). There were excellent correlation of LV EF and mass between CT and CMR (both $r = 0.94$).

3.2. Comparison between CT noise reduction strategies and CMR

The patients with CT tube current modulation ($n = 24$) were used to test the effect of NR as compared to CMR. There was excellent correlation in LV EF and LV mass in all three NR strategy groups compared to CMR (LVEF: No NR $r = 0.94$, low NR $r = 0.96$, high NR $r = 0.99$; all $p < 0.001$) and LV mass: all groups $r = 0.99$ (all $p < 0.001$).

On Bland–Altman analysis between CT noise reduction strategies and CMR, there was an improved limits of agreement in studies with high NR for LV EF compared to no and low NR strategies. As shown in Fig. 3, although there was systemic underestimation of LV mass by CT (no NR -10.3 ± 10.1 g, low NR -10.3 ± 12.5 g) compared to CMR, the underestimation was attenuated in studies when high NR was implemented (-0.5 ± 8.3 g).

Intra and inter-observer reproducibility was best with high NR for LV EF and mass assessment (Table 2).

3.3. Effect of noise reduction strategies on contrast to noise ratio

Studies without NR had lower CNR compared to studies with low and high levels of NR at both the ES phase (no NR 8.3 ± 4.2 , low NR 13.3 ± 6.8 , high NR 18.1 ± 9.9 ; all $p < 0.01$) and ED phase (no NR 6.2 ± 3.8 , low NR 10.6 ± 6.1 , high NR 14.1 ± 7.7 ; all $p < 0.01$) (Fig. 4).

4. Discussion

In this study, we found excellent correlations for LV EF and LV mass assessed between cardiac CT and CMR. The application of a novel noise reduction strategy on cardiac CT datasets performed with tube current modulation showed an improvement in CNR with increasing strengths of NR as well as an improvement in the limit of agreement for the assessment of LV EF. When implementing a high NR strategy, the degree of systemic

underestimation of LV mass compared to CMR was markedly reduced, with the best inter- and intra-observer reproducibility for LV EF and mass assessment.

Cardiac CT is emerging as an alternative imaging modality for assessment of LV EF and mass, in particularly in patients who cannot undergo CMR due to contraindications or in patients with poor acoustic window [10]. Retrospective ECG gated acquisition of functional CT datasets are needed to obtain appropriate ES and ED phases for the calculation of LV EF. Several studies have confirmed that this method without tube current modulation is feasible and correlates well with LV EF measured using CMR [9,14–16]. Furthermore, improvements in spatial and temporal resolution with cardiac CT have led to increased accuracy for the assessment of LV EF. However radiation exposure remains a concern regarding retrospectively-gated scan acquisition.

Tube current modulation provides a method for reducing radiation dose as evident from our results, but at the expense of increased image noise. In this study we used a novel phase NR strategy to investigate whether NR in tube modulated CT datasets improves the accuracy and reproducibility in LV EF and mass measurements. The NR algorithms used in this study take advantage of voxel data available from adjacent phases at ES and ED. The software performs deformable registration to anatomically align voxels from each phase to its adjacent phases and applies the NR algorithm between phases to reduce noise while preserving anatomical detail. Higher degree of NR is possible when data is obtained from more than one neighboring phase. An improvement in CNR indicating better image quality is seen with application of this noise reduction strategy. The advantage of this phase-based NR strategy is that it is applied after the acquisition of the images offline in DICOM format during the post-processing stage, thus negating the need for access of the CT raw data.

Moreover, we found a graded increase in CNR with increasing strength of NR level applied. With the improved CNR using high NR, we found an improvement in the limit of agreement and reproducibility for LV EF as assessed with cardiac CT with tube current modulation. A study which uses tube current modulation dual source CT identified increased image noise as the reason for discrepant ratings of myocardial wall contraction when compared to CMR [17]. For certain patient populations such as those with systolic LV dysfunction being considered for device-based therapy, accurate assessment of LV EF by CT is imperative when other imaging modalities are inadequate (i.e. poor acoustic window in echocardiography or contraindication to CMR) and may impact on clinical decision making [18]. Misclassification of patients eligibility for device therapy based on LV EF assessment may result in inappropriate implantation contributing to increase economic costs or under treatment of otherwise eligible patients. [19]

We also found that LV mass assessment was improved with the application of high NR, with reduced systematic underestimation of bias between CT and CMR as well as improved reproducibility. We found a higher degree of bias (average underestimation of 10 g) for assessing LV mass without NR or with a low level of NR when compared with other studies (bias of 3.6–6.2 g) which did not apply tube current modulation during CT acquisition [9,15,16]. In this study, this bias is significantly reduced with high NR, with a modest improvement in the degree of agreement. LV mass measurement is of clinical significance as the presence of left ventricular hypertrophy is associated with worse prognostic outcomes and would warrant intensification of anti-hypertensive regimen [20,21].

4.1. Limitations

While we used 3 different CT scanners, we found excellent correlation with CT and CMR measures of LV parameters. Our sample size is small, which limits our ability to assess the effect of noise reduction by scanner type. Furthermore, the temporal and spatial resolution

between CT and CMR are not identical, though despite this we found excellent correlation between the imaging modalities. Although ECG-pulsing in retrospective mode leads to reduce radiation dose, other CT modes such as prospective or high pitch scanning will result in even lower radiation dose if LV EF data is not required. Scanning in retrospective mode is required to ensure end diastolic and end systolic phases were acquired.

4.2. Conclusion

The application of novel phase based noise reduction strategy results in improvement in image quality and assessment for LV parameters. A high NR strategy on tube current modulated functional cardiac CT improves correlation of EF compared to CMR and reduces variability of EF and mass evaluation by increasing the CNR. In an effort to reduce radiation dose with tube modulation, this strategy provides better image quality when LV function and mass quantification is needed.

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Fig. 1.

Diagram showing noise reduction strategy with low noise reduction where each phase uses data from two neighboring phases for noise reduction strategy and high noise reduction where each phase received data from 4 neighboring phases.

Fig. 2.

An example of a CT image left ventricular short axis slice at end diastole from a patient with no noise reduction (A), low noise reduction (B), and high noise reduction (C) and corresponding cardiac magnetic resonance (CMR) short axis slice (D).

Fig. 3.

Bland–Altman analysis for LV EF using no noise reduction (A), low noise reduction (B) and high noise reduction strategies (C), for LV Mass using no noise reduction (D), low noise reduction (E) and high noise reduction strategies (F).

Fig. 4.

Bar graph showing an improvement in contrast to noise ratio (CNR) with higher level of noise reduction (NR) at both end systole and end diastole.

Table 1

Patient characteristics and imaging parameters/measurements of overall cohort and subgroup performed with tube current modulation.

	Total N = 40	Tube-modulated N = 24
Patient characteristics		
Age (years)	42.4 ± 14.8	40.8 ± 13.9
Male	26 (65%)	16 (67%)
BMI (kg/m ²)	30.0 ± 9.2	31.0 ± 10.8
Beta Blocker	25 (63%)	16 (67%)
HR (BPM)	70.8 ± 12.4	67.8 ± 11.8
CMR measurements		
CMR LV ESV (mL)	103.2 ± 102.1	96.7 ± 84.2
CMR LV EDV (mL)	179.7 ± 98.3	181.0 ± 90.8
CMR LV EF (%)	51.0 ± 15.3	51.4 ± 14.4
CMR LV mass (g)	146.8 ± 68.0	148.0 ± 71.9
CT measurements		
CT LV ESV (mL)	108.9 ± 93.0	107.0 ± 85.7
CT LV EDV (mL)	194.5 ± 94.5	199.6 ± 86.1
CT LV EF (%)	49.6 ± 14.8	51.2 ± 14.2
CT LV mass (g)	158.0 ± 72.0	158.3 ± 71.8

BMI, body mass index; HR, heart rate; BPM, beats per minute; CNR, contrast-to-noise ratio; CMR, cardiac magnetic resonance; CT, computed tomography; LV, left ventricular; ESV, end systolic volume; EDV, end diastolic volume; EF, ejection fraction.

Table 2

Interobserver and intraobserver reproducibility of CT assessment with various noise reduction strategies on LV EF and Mass.

	Intraobserver		Interobserver	
	Absolute difference*	Percentage difference	ICC [§]	Percentage difference
L VEF				
No NR	1.6 ± 4.2%	3.3%	0.949	2.7%
Low NR	1.6 ± 2.7%	3.3%	0.973	2.9%
High NR	0.4 ± 2.2%	0.8%	0.989	0.5%
LV Mass				
No NR	8.2 ± 16.3 g	4.9%	0.967	10.5%
Low NR	7.3 ± 9.8 g	4.4%	0.984	12.1%
High NR	1.3 ± 7.5 g	0.8%	0.994	0.2%

NR, Noise reduction; ICC, intraclass correlation coefficient.

* All $P > 0.05$,

[§] $P < 0.001$.