Choosing the Adaptive Cardiac Phase for Assessing Cardiac Dimensions Using Cardiac Computed Tomography for Heart Disease

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Abstract

Background Choosing a suitable cardiac cycle to measure cardiac chamber dimensions and wall thickness can be a more accurate assessment of cardiovascular disease.

Methods Cardiac CT was performed on 137 patients for suspected coronary disease. The parameters of left atrium (LA), left ventricle (LV), right atrium (RA), and right ventricle (RV), as well as the wall thickness of LV were measured in different cardiac phases. The general linear mixed model was used to analyze differences in different phases and the correlation between these parameters and traditional risk factors. ROC analysis was performed to estimate LA enlargement.

Results The dimensions of LA, RA, and LV wall thickness achieved the maximum at the phase of 35–45%, and those of LV and RV, at 95–5%. Whereas, the changes of LA-B (antero-posterior diameter), LV-D1 (basal dimension), RA-B (minor dimension) and RV-D2 (mid cavity dimension) were relatively more stable during the cardiac cycle. The maximum LA-B diameter(95%CI 36.92,38.48mm), LV-D1 diameter(95%CI 44.36,45.83mm), RA-B diameter(95%CI 48.75,50.61mm), and RV-D2 diameter(95%CI 30.83,32.84mm) and the maximum interventricular septum thickness(95%CI 10.79,11.51mm) was acquired. Heart rate (HR) and smoking were potential indicators of LVD2 (mid cavity dimension), while HR and LV myocardial mass were potential indicators of LVD3 (apical-basal dimension). In phase 45%, the cut-off value of LA-B was 37.12mm has high sensitivity of 90.9% for predicting LA enlargement.

Conclusion Cardiac chamber dimensions and wall thickness vary with the cardiac phase. Choosing the adaptive cardiac phase for evaluating these parameters obtained by cardiac CT could provide a more accurate clinical measurement.

Trial registration retrospectively registered.

1. Introduction

The heart is a hollow organ at the center of the circulatory system. Rhythmic contractions and dilations by the contraction of myocardial cells pump the blood. Cardiac remodeling is an important pathological process in the occurrence and development of various heart diseases, not only changes in the diameter of the cardiac chambers but also changes in the thickness of the ventricular wall. These conditions can remain clinically silent until late in their progression. Therefore, it is important to recognize changes in cardiac chamber dimensions and wall thickness early in the course of these diseases. In addition, assessing the dimensions of the cardiac chambers is useful for diagnosis of cardiac disease, risk stratification, and therapeutic decision making. For example, left atrial (LA) enlargement is associated with an increased risk of adverse cardiovascular events, such as atrial fibrillation (AF), myocardial infarction, congestive heart failure, and stroke[1, 2]. Left ventricular (LV) enlargement is associated with an array of cardiac pathologies, including cardiomyopathy, ischemia, and valvular heart disease. Moreover, right heart function and diameter are independent determinants of clinical status and prognosis in many congenital and acquired disease states. Therefore, obtaining accurate diameters of cardiac chambers and wall thickness are crucial to clinical decision-making and follow-up for cardiac diseases.

It is well-known that cardiac chamber dimensions and LV wall thickness change with the cardiac cycle, and many studies have confirmed that cardiac diameters differ in systole and diastole[3, 4]. However, the cardiac diameters are usually measured during a random phase of the cardiac cycle, and the result might be the largest or the smallest or in the between. This can especially affect the choice of ablation method for patients with AF and the prognosis after ablation. The dimension of the LA, especially the maximum diameter of the antero-posterior diameter (LA-B) is used as a parameter of ablation method and the prognosis after ablation. Some research has shown that cryoballoon (CB) ablation may be recommended for patients with LA-B $\leq$ 4cm, while radiofrequency (RF) would be more appropriate for patients with LA-B >4cm[5]. Therefore, it is also crucial to choose an accurate cardiac phase to measure the dimensions of the cardiac chamber. Echocardiography is the most commonly used noninvasive modality for evaluating the size of the cardiac chambers, but it is heavily dependent on the sonographer's skills and has poor repeatability. Cardiac MRI is considered the reference standard for evaluating cardiac size and function, but it is costly and time-consuming[6]. Moreover, cardiac MRI is rarely performed as an initial investigation for evaluating cardiac size. Multi-slice spiral computed tomography (CT) combined with retrospective electrocardiography (ECG) gating could provide heart images with high time resolution and reconstruct multi-phase images of the whole cardiac cycle[7, 8]. It can comprehensively evaluate lesions that cause the heart to enlarge for many reasons, and is emerging as a promising tool with respect to quantifying chamber volumes and cardiac structure[9, 10]. Therefore, it is recommended to use the technology of ECG gated CT acquisition for evaluating the diameter of cardiac chamber(especially LA-B) accurately instead of motion artifacts.

In recent years, many scholars have focused cardiac chamber dimensions changed just on end-systole and end-diastole phase[3, 4]. Moreover, different researchers have set different time points for systole and diastole in the cardiac cycle. This makes the assessment of the cardiac chamber dimensions inconsistent in the cardiac phase and results in different dimensions for the same structure, especially different heart rate. Therefore, the aim of our study was to assess the dynamic changes of the normal cardiac chamber dimensions and wall thickness in ten cardiac phases, which is used to compare abnormal cardiac disease. While we obtained a threshold for judging left atrium enlargement in CT image.

2. Methods

This study was conducted in accordance with the Declaration of Helsinki (as was revised in 2013), and an application for the exemption of patients' informed consent was approved by the Institutional Review Board of our hospital, due to the retrospective nature of the study. So all written informed consent forms are waived.

2.1 Patient selection

Two hundred consecutive patients underwent cardiac CT scans for suspected coronary disease between August and December 2019. Patients with normal cardiac chamber dimensions or LA enlargement on echocardiography (within three months of the CT study) and who were at least 18 years of age were enrolled. Exclusion criteria included patients with severe arrhythmia, pacemakers, cardiovascular surgical procedures, known heart disease and motion artifact. Patients with structural or functional abnormalities of the heart detected by echocardiography were also excluded.

2.2 CT scanning protocol

All CT angiography (CTA) scans were acquired using a 256-slice scanner (Philips Brilliance iCT; Philips Medical Systems, Cleveland, OH, USA) with retrospective ECG-gating. The scanning range is from the bifurcation of the pulmonary artery to the level of the diaphragm with a thickness of 0.5 cm. The scan is automatically triggered by setting the region of interest in the descending aorta (the threshold value was set as 250 Hounsfield units [Hu]). A high-pressure syringe was used to inject 75–85 mL of contrast agent (Iopamidol 370 mg/mL) through the elbow vein. Subsequently, 40 mL of physiological saline was injected at the same rate with a flow rate of 5.0–5.5 mL/s. We used 120 kV for patients with body weight ≥ 75 kg, 100 kV for patients with body weight < 75 kg, 1200 mAs/slice for patients with body mass index (BMI) ≥ 24 , and 900 mAs/slice for patients with BMI < 24 .

2.3 Image analysis

Multi-phase reconstructions were done from 5–95% in increments of 10% on a 256-slice spiral CT scanning workstation. The reconstruction window of 10 cardiac cycles was extended to the entire thorax. All images were transferred to a post-processing workstation (Philips Intelli Space Portal system) and loaded into the cardiac viewer application. Two experienced observers (both with three years of experience in the interpretation of cardiac CT images) who were blinded to the echocardiographic data independently reviewed the reconstructed CT images on a dedicated post-processing workstation.

The left atrial maximum transverse diameter (LA-A) and antero-posterior diameter (LA-B) were to be traced manually on an image showing the right inferior pulmonary vein insertion[11]. The thoracic vertebral diameter was measured at the same level[12]. The left atrial-vertebral ratio (LAssVR) was then obtained by dividing the LA diameter by the vertebral diameter (Fig. 1A). The left ventricular basal dimension (LVD1), mid cavity dimension (LVD2) and apical-basal dimension (LVD3) in different cardiac phases were measured in the long-axis view of LV[13] (Fig. 1D). LV wall thickness(including 16 segmentations) at the basal, mid, and apical segments in different cardiac phases were measured in the short-axis view of the LV (Fig. 1C). The right atrial major dimension (RA-A), minor dimension (RA-B), right ventricular basal dimension (RVD1), mid cavity dimension (RVD2), and apical-basal dimension (RVD3) in different cardiac phases were measured in the apical four-chamber multiplanar reconstruction view[14, 15] (Fig. 1B).

2.4 Statistical analysis

The statistical software package R (Version 3.6.1; R Core Team, 2019) was used to perform analyses. Qualitative data were expressed by frequency and percentage, while quantitative data were expressed by mean $\pm$ standard deviation. Differences in wall thickness and cardiac chamber dimensions between cardiac cycles were detected using linear mixed model. The relationship between LV-D2/LV-D3 and clinical characteristics were also estimated by linear mixed model. ROC analyze together with area under curve, sensitivity and specificity were used to estimate the diagnosis value of single and combined parameters for left atrial enlargement. Intra- and inter-observer variability for reproducibility were assessed using intraclass correlation coefficient (ICCs). The significance level was set at $p < 0.05$.

3. Results

3.1 Baseline characteristics

We enrolled a total of 126 subjects (65 males and 61 females, mean age 55 years, range 47–77 years) with normal chamber dimensions and 118 subjects (61 men and 57 women, mean age 54 years, range 30–77 years) with normal wall thickness, 11 patients(6 men and 5 women, mean age 58 years, range 55–74 years) with LA enlargement. Table 1 shows the clinical characteristics of the study population.

Table 1
General clinical characteristics

Characteristics	NCD group (N = 126)	NWT group (N = 118)	LAE group (N=11)
Age(years)	55.52 ± 11.38	54.89 ± 11.18	64.5 ± 7.74
Sex(male;n,%)	65(51.6%)	61(51.7%)	6(54.5%)
BMI (kg/m ²)	23.95 ± 2.68	24.17 ± 2.70	23.63 ± 2.29
BSA(m ²)	1.65 ± 0.16	1.65 ± 0.15	1.67 ± 0.17
Smoking(n,%)	30(23.8%)	29(24.6%)	2(18.2%)
Drinking(n,%)	22(17.5%)	21(17.8%)	1(9%)
Hypertension(n,%)	34(27.0%)	30(25.4%)	5(45.5%)
Hyperglycemia(n,%)	15(11.9%)	15(12.7%)	1(9%)
Hyperlipemia(n,%)	32(25.4%)	31(26.3%)	3(27.3%)
HR(Beats/min)	62.98 ± 8.67	62.98 ± 8.72	64.64 ± 20.5
LVMM(g)	111.07 ± 26.75	110.39 ± 24.09	117.34 ± 33.14
BMI indicates body mass index; BSA,body surface area;HR,heart rates; LVMM,LV-myocardial mass; NCD,normal chamber dimensions; NWT,normal wall thickness			

3.2 LA parameters in different cardiac cycles

Table 2 list the mean ± sd of LA-A, LA-B, and LAVR in different cardiac phases, Fig. 2A shows the change trends. For LA-A, LA-B, and LAVR, the maximum and minimum values were observed in the 35–45% phase and 5% phase, respectively. The maximum values of LA-A and LA-B were 67.03 ± 5.39 mm and 37.70 ± 4.40 mm respectively. The minimum value of LA-B was 29.54 ± 4.43 mm. The variation of LA-B in cardiac cycles was of statistical significance, LA-A and LAVR were not. Compared with LA-A, LA-B changes more stably during the cardiac cycle.

Table 2
Cardiac chamber dimensions in different cardiac cycles

Phase	LA-A	LA-B	LAVR	LV-D1	LV-D2	LV-D3	RA-A	RA-B	RV-D1	RV-D2	RV-D3
5%	54.26 ± 6.28	29.54 ± 4.43	1.77 ± 0.24	45.09 ± 4.16	50.44 ± 4.73	77.36 ± 8.36	39.46 ± 5.72	36.95 ± 4.84	42.13 ± 5.19	31.28 ± 5.19	74.35 ± 7.96
15%	56.24 ± 5.90	30.71 ± 4.69	1.84 ± 0.24	43.80 ± 4.69	45.99 ± 6.16	74.75 ± 7.04	42.24 ± 5.51	40.55 ± 5.29	41.70 ± 5.24	29.68 ± 4.95	71.06 ± 7.26
25%	61.49 ± 5.65	33.71 ± 4.52	1.90 ± 0.30	41.06 ± 4.67	37.98 ± 6.69	66.57 ± 7.47	44.55 ± 5.50	45.24 ± 5.45	38.60 ± 4.97	25.90 ± 4.87	65.21 ± 7.32
35%	65.74 ± 5.60	36.52 ± 4.44	1.92 ± 0.29	38.64 ± 4.85	30.89 ± 7.23	58.94 ± 8.38	45.37 ± 5.50	48.62 ± 5.27	36.13 ± 5.35	23.17 ± 4.99	60.11 ± 7.55
45%	67.03 ± 5.39	37.70 ± 4.40	1.91 ± 0.29	37.55 ± 5.43	31.15 ± 7.97	58.77 ± 8.36	45.58 ± 5.18	49.68 ± 5.26	36.00 ± 5.89	23.44 ± 5.40	58.63 ± 7.33
55%	63.99 ± 6.22	35.51 ± 5.07	1.90 ± 0.29	40.16 ± 5.57	39.88 ± 8.05	66.16 ± 9.53	44.90 ± 5.68	45.27 ± 5.77	39.07 ± 6.18	27.22 ± 5.85	63.02 ± 8.29
65%	61.22 ± 5.91	33.91 ± 4.65	1.88 ± 0.28	41.84 ± 4.47	44.56 ± 6.10	70.55 ± 7.51	45.01 ± 5.22	42.62 ± 5.25	41.15 ± 6.11	29.36 ± 6.04	65.92 ± 8.14
75%	60.52 ± 5.66	33.94 ± 4.33	1.85 ± 0.26	42.62 ± 4.17	45.42 ± 6.34	71.59 ± 7.39	44.56 ± 5.47	41.96 ± 4.84	41.20 ± 5.92	29.92 ± 5.96	67.28 ± 7.69
85%	59.69 ± 5.93	33.97 ± 4.22	1.82 ± 0.26	43.40 ± 4.19	46.56 ± 5.71	72.86 ± 7.10	43.76 ± 5.48	41.00 ± 4.83	41.40 ± 5.79	30.22 ± 5.71	68.54 ± 7.81
95%	55.62 ± 6.07	31.53 ± 4.75	1.80 ± 0.38	44.91 ± 4.07	49.66 ± 5.17	76.37 ± 7.25	39.44 ± 5.45	36.77 ± 5.02	41.95 ± 5.56	31.83 ± 5.69	73.50 ± 8.22
t	1.858	6.601	-0.317	2.938	6.699	3.700	1.624	-4.603	4.885	7.889	0.669
p-value	0.063	<0.001	0.752	0.003	<0.001	<0.001	0.105	<0.001	<0.001	<0.001	0.504
The parameters were expressed as mean values ± standard deviations. LA-A—left atrial maximum transverse diameter; LA-B—left atrial antero-posterior diameter; LAVR—left atrial-vertebral ratio; LV-D1—Left ventricular basal dimension; LV-D2—left ventricular mid cavity dimension; LV-D3—left ventricular apical-basal dimension; RA-A—right atrial major dimension; RA-B—right atrial minor dimension; RV-D1—right ventricular basal dimension; RV-D2—right ventricular mid cavity dimension; RV-D3—right ventricular apical-basal dimension											

In phase 45%, the cut-off value of LA-A was 77.57mm with 36.4% sensitivity, 97.6% specificity, 57.1% positive prediction value, 94.6% negative prediction value. The cut-off value of LA-B was 37.12mm with 90.9% sensitivity, 37.6% specificity, 13.2% positive prediction value, 98.4% negative prediction value. And the combined diagnosis of LA-A and LA-B had 45.5% sensitivity, 98.4% specificity, 71.4% positive prediction value, 95.4% negative prediction value. Besides, LAVR had 1.845 cut-off value with 81.8% sensitivity, 52.4% specificity, 13% positive prediction value, 97.1% negative prediction value.

3.3 LV parameters in different cardiac cycles

Table 2 list the mean ± sd of LV chamber dimensions (LVD1, LVD2, LVD3) in different cardiac phases, Fig. 2A shows the change trends. The maximum and minimum values of LV dimensions were observed in the 5% phase and 35–45% phase, respectively. The maximum values of LV-D1, LV-D2, and LV-D3 were 45.09 ± 4.16 mm, 50.44 ± 4.73 mm, and 77.36 ± 8.36 mm, respectively. The variation of LV-D1, LV-D2, and LV-D3 in cardiac cycles was of statistical significance. Of these diameters, LV-D1 showed the most stable changes during the cardiac cycle.

Results from univariate analysis revealed that body surface area (BSA), heart rate (HR), LV-myocardial mass (LVMM), smoking, and diabetes were significantly related to LV-D2 and LV-D3 (Table 3). Multivariate analysis demonstrated that HR and smoking were potential indicators of LV-D2, and that HR and LVMM were potential indicators of LV-D3. One unit change in HR was associated with 0.187 unit decrease in the LV-D2. The average LV-D2 of smokers is 2.830 mm higher than that of non-smokers. The other variables were not significantly related to LV-D2. One unit change in HR was associated with 0.164 unit decrease in the LV-D3, while one unit change in LVMM was associated with 0.124 unit increase in the LV-D3.

Table 3
the univariate analysis of potential related factors for LVD2 and LVD3

Characteristics	LV-D2	t	p-value	LVD3	t	p-value
Age	0.021	0.482	0.631	-0.175	-3.256	0.001
BMI	0.149	0.804	0.423	-0.082	-0.346	0.730
BSA	8.500	2.750	0.007	14.096	3.642	< 0.001
HR	-0.222	-4.130	< 0.001	-0.231	-3.288	0.001
LVMM	0.058	3.242	0.002	0.140	6.965	< 0.001
Smoker	41.29 ± 9.30	3.631	< 0.001	68.58 ± 10.16	2.352	0.020
No	45.34 ± 8.63			72.00 ± 9.37		
Yes						
Drinker	41.96 ± 9.03	1.231	0.221	68.87 ± 10.16	1.838	0.068
No	43.63 ± 10.44			71.88 ± 9.28		
Yes						
Hypertension	42.14 ± 9.43	0.402	0.688	69.47 ± 10.42	-0.175	0.861
No	42.56 ± 8.98			69.19 ± 9.11		
Yes						
Diabetes	42.62 ± 9.34	-2.040	0.044	69.68 ± 10.15	-1.231	0.221
No	39.52 ± 8.62			67.28 ± 9.29		
Yes						
Dyslipidemia	41.88 ± 9.28	1.315	0.191	69.34 ± 10.15	0.156	0.876
No	43.37 ± 9.30			69.56 ± 9.87		
Yes						
Abbreviations as in Table 1						

Table 4 lists the mean ± sd of LV wall thickness at the basal, mid, and apical segments in different cardiac phases. Figure 2B-C shows the change trend graph of LV wall thickness. The LV wall thickness achieved the minimum at the phase of 95–5%, and the maximum at 35–45%. The maximum values of the interventricular septum (Septum), anterior (Ant), antero-lateral (Ant-Lat), infero-lateral (Post-Lat), and inferior (Inf) at the basal segment were 10.80 ± 1.47 mm, 11.82 ± 2.46 mm, 11.87 ± 2.49 mm, 12.03 ± 2.32 mm, and 10.75 ± 2.10 mm, respectively. The variation of Ant and Ant-Lat in cardiac cycles were of statistical significance. The maximum values of Septum, Ant, Ant-Lat, Post-Lat, and inferior Inf at the mid segment were 11.15 ± 1.98 mm, 10.22 ± 2.53 mm, 10.75 ± 2.88 mm, 10.93 ± 2.56 mm, and 11.89 ± 2.39 mm, respectively. The variation of Septum, Ant, Ant-Lat, Post-Lat, Inf in cardiac cycles was of statistical significance. The maximum values of Septum, Ant, Ant-Lat, and Inf at the apical segment were 9.42 ± 2.19 mm, 10.83 ± 2.31 mm, 10.60 ± 2.14 mm, and 9.15 ± 2.03 mm, respectively. The variation of Septum, Ant, Ant-Lat, and Inf in the cardiac cycles were of statistical significance. In the three segments, the wall changes of the basal segment were the more stable than middle and apical segments.

Table 4
Left ventricular wall thickness in different cardiac cycles

Basal						Mid					Apical			
Phase	Septum	Ant	Ant-Lat	Post-Lat	Inf	Septum	Ant	Ant-Lat	Post-Lat	Inf	Septum	Ant	Ant-Lat	Inf
5%	7.76 ± 1.09	7.04 ± 1.30	7.38 ± 1.12	7.55 ± 1.19	7.52 ± 1.31	7.93 ± 1.59	6.08 ± 1.14	6.53 ± 1.04	6.63 ± 1.03	7.69 ± 1.30	5.93 ± 1.46	6.89 ± 1.36	6.61 ± 1.24	5.54 ± 1.15
15%	8.29 ± 1.18	7.45 ± 1.46	7.82 ± 1.42	7.73 ± 1.35	7.69 ± 1.33	8.48 ± 1.80	6.53 ± 1.14	7.02 ± 1.23	7.18 ± 1.27	8.18 ± 1.40	6.52 ± 1.79	7.66 ± 1.52	7.34 ± 1.57	5.88 ± 1.34
25%	9.60 ± 1.33	9.31 ± 2.23	9.28 ± 1.98	9.34 ± 1.88	8.90 ± 1.80	9.82 ± 2.02	8.19 ± 1.90	8.51 ± 2.06	8.79 ± 1.86	10.04 ± 2.08	7.79 ± 2.03	9.04 ± 1.94	8.94 ± 1.84	7.44 ± 1.83
35%	10.61 ± 1.45	11.82 ± 2.46	11.61 ± 2.59	11.41 ± 2.37	10.07 ± 1.94	11.15 ± 1.98	10.22 ± 2.53	10.75 ± 2.84	10.93 ± 2.56	11.89 ± 2.39	9.42 ± 2.19	10.79 ± 2.16	10.60 ± 2.14	9.15 ± 2.03
45%	10.80 ± 1.47	11.19 ± 2.63	11.87 ± 2.49	12.03 ± 2.32	10.75 ± 2.10	10.75 ± 1.98	9.48 ± 2.28	10.75 ± 2.88	10.79 ± 2.70	11.40 ± 2.47	9.39 ± 2.07	10.83 ± 2.31	10.51 ± 2.30	8.73 ± 2.16
55%	10.24 ± 1.58	9.05 ± 2.09	9.56 ± 3.31	9.35 ± 2.01	9.65 ± 4.13	9.29 ± 1.88	7.45 ± 1.45	7.93 ± 1.79	8.00 ± 2.06	9.04 ± 2.10	7.28 ± 1.78	8.71 ± 3.62	8.40 ± 2.01	6.95 ± 1.89
65%	9.22 ± 1.34	8.23 ± 1.57	8.49 ± 1.45	8.95 ± 1.51	8.71 ± 1.49	8.63 ± 1.66	6.67 ± 1.18	7.06 ± 1.24	7.13 ± 1.26	8.47 ± 1.52	6.61 ± 1.66	7.64 ± 1.55	7.47 ± 1.50	6.35 ± 1.49
75%	8.85 ± 1.32	7.93 ± 1.44	8.19 ± 1.19	8.86 ± 3.78	8.57 ± 1.44	8.45 ± 1.68	6.47 ± 1.15	6.91 ± 1.17	7.07 ± 1.31	8.47 ± 1.55	6.53 ± 1.68	7.57 ± 1.66	7.35 ± 1.63	6.30 ± 1.49
85%	8.59 ± 1.19	7.73 ± 1.45	8.26 ± 3.62	8.31 ± 1.37	8.28 ± 1.33	8.27 ± 1.62	6.29 ± 1.10	6.73 ± 1.08	7.16 ± 3.83	8.17 ± 1.43	6.38 ± 1.67	7.35 ± 1.63	7.16 ± 1.62	6.07 ± 1.48
95%	8.02 ± 1.22	7.03 ± 1.14	7.66 ± 1.12	7.85 ± 1.26	7.61 ± 1.27	7.81 ± 1.63	5.93 ± 0.95	6.38 ± 0.98	6.54 ± 0.99	7.72 ± 1.28	5.89 ± 1.48	6.87 ± 1.53	6.65 ± 1.41	5.60 ± 1.21
t	-1.892	-5.248	-2.879	-1.571	-0.596	-7.641	-8.179	-7.447	-6.332	-6.541	-6.940	-6.388	-7.132	-5.404
p-value	0.059	< 0.001	0.004	0.117	0.551	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Septum—interventricular septum; Ant—anterior; Ant-Lat— antero-lateral; Post-Lat—infero-lateral; Inf—inferior														

3.4 RA parameters in different cardiac cycles

Table 2 list the mean ± sd of the right atrial major dimension (RA-A) and the mean values of the RA minor dimension (RA-B) in different cardiac phases, while Fig. 2C shows the change trends. For RA-A and RA-B, the maximum and minimum values were observed in the 45% phase and 95% phase, respectively. The maximum values of RA-A and RA-B were 45.58 ± 5.18 mm and 49.68 ± 5.26 mm, respectively. The variations of RA-B in cardiac cycles were of statistical significance, while the variations of RA-A in cardiac cycles were non-significant. Compared with RA-A, RA-B changes more stably during the cardiac cycle.

3.5 RV parameters in different cardiac cycles

Table 2 list mean ± sd of the RV chamber dimensions (RVD1, RVD2, RVD3) in different cardiac phases. The maximum and minimum values of RV dimensions were observed in the 95–5% phase and 35–45% phase, respectively. The maximum values of RV-D1, RV-D2, and RV-D3 were 42.13 ± 5.19 mm, 31.83 ± 5.69 mm and 74.35 ± 7.96 mm, respectively. The variation of RV-D1 and RV-D2 in cardiac cycles was of statistical significance, while the variation of RV-D3 in cardiac cycles was non-significant. Among these diameters, RV-D2 showed the most stable changes during the cardiac cycle.

In addition, the comparison of clinical characteristics and cardiac parameters between male and female subjects revealed significant discrepancy in individual characteristics, including age, BSA, HR, LVMM, smoking, drinking, and diabetes. These differences were also significantly related to gender. Upper and lower reference limits were higher in men than in women. Therefore, we generated cardiac parameters reference ranges on cardiac CT in different cardiac phases for both genders for our population in supplemental material.

3.6 Reproducibility

Inter- and intraobserver ICCs were determined randomly among 126 patients. Interobserver ICCs of 0.913 for LA-A, 0.920 for LA-B, 0.935 for LV-D1, 0.926 for LV-D2, 0.917 for LV-D3, 0.925 for RA-A, 0.921 for RA-B, 0.936 for RV-D1, 0.956 for RV-D2 and 0.941 for RV-D3 were obtained. Also, intraobserver ICCs of 0.902 for LA-A, 0.912 for LA-B, 0.928 for LV-D1, 0.915 for LV-D2, 0.903 for LV-D3, 0.901 for RA-A, 0.907 for RA-B, 0.924 for RV-D1, 0.917 for RV-D2 and 0.916 for RV-D3 were obtained.

4. Discussion

This is the first study to conduct a detailed dynamic evaluation of the cardiac chamber dimensions and wall thickness with the reconstruction of ten cardiac phases in whole cardiac cycle. This allows us to choose the correct cardiac phase for measuring the maximum diameter required to predict the occurrence and recurrence of cardiac disease. The dimensions of the cardiac chamber and wall thickness changes dynamically in different cardiac phases and match the physiological phase of that cycle[16]. We also found that LA-B, LV-D1, RA-B and RV-D2 were more stable than other diameters in the cardiac cycle. Therefore, we believe that the four diameters are most suitable for evaluating the condition of the heart on noncardiac CT images.

LA size is a marker of the severity and chronicity of diastolic dysfunction[17]. These LA diameters measured on a conventional axial cross-section can be used for detecting of patients with possible LA enlargement on routine chest CTA, prompting confirmatory evaluation with echocardiography. Stoyan Popkirov proposed that Coronary CTA should be performed in patients with acute stroke, and that the measurement of chest echocardiography was not accurate, indicating the importance of CT measurement of LA enlargement[18]. Atrial fibrillation (AF) is the most common cardiac arrhythmia encountered in clinical practice. LA enlargement is associated with atrial remodeling, which is associated with recurrence of atrial fibrillation after radiofrequency catheter ablation (RFCA). LA-B is an independent predictor of AF recurrence. While some studies have shown that the larger or smaller the LA-B has the higher the prevalence of AF recurrence[19–21]. We found that the LA-B value varies greatly between 29.54 ± 4.43 mm and 37.70 ± 4.40 , rather than staying constant throughout the whole cardiac cycle, which might mean that changes of LA-B value in the cardiac cycle should be taken into account when evaluating radiofrequency ablation in patients with atrial fibrillation by using the LA-B maximum value. Selecting appropriate phase for LA-B measurement is more conducive to the choosing of appropriate ablation method and the prediction of AF recurrence. Cryoballoon (CB) and radiofrequency (RF) are common methods of ablation. Given the short procedure time and efficacy, CB ablation may be recommended for patients without enlarged LA, while RF would be more appropriate in large LA size [22]. MDCT of the pulmonary veins and LA provides the necessary anatomic information for successful CB and RF catheter ablation [23]. At the same time, choosing phase 35% and 5% to measure LA-B is of great significance, and the LA volume can also be obtained. LAssVR is a simple new measure directly scaling the left atrial diameter to the anthropomorphic characteristics of the patient. With the use of ROC analysis, cardiac CT measurements that provided a optimal test characteristics for identifying LAE by echocardiography as the reference standard were determined.

LV is an integral part of the heart's pumping function. Historically, linear dimension of LV was measured at the base of the LV in the long-axis view. However, the base of the LV does not reflect the true (maximal) diameter of the ellipsoid mode, leading to underestimation of chamber size[24]. Measurement of linear dimensions at the midventricular level (LV-D2) better reflects the ellipsoid geometry of the LV cavity and provides a more accurate estimate of LV mass and size as compared with the traditionally recommended basal level[13]. In addition, the LV contains obliquely-oriented myofibers superficially, longitudinally-oriented myofibers in the subendocardium, and predominantly circular fibers in between. This contributes to the more complex movement of the LV, including torsion, translation, rotation, and thickening[25]. It is difficult to comprehensively evaluate the size of the chamber using a single diameter measurement method. Therefore, in this study, we measured three dimensions of LV in different cardiac phases. Multivariate analysis demonstrated that HR and smoking are potential indicators of LV-D2. HR and LVMM are potential indicators of LV-D3.

Cardiac remodeling is an important pathological process in the occurrence and development of various cardiovascular diseases such as essential hypertension and cardiomyopathy, including changes in the cardiac chamber dimensions and the wall thickness. The ventricular septum is the central structure of both ventricles. The helical ventricular band model explains the close relationship between biventricular function and ventricular septum[26]. Perhaps this is one of the reasons why myocardial wall hypertrophy first appears as ventricular septal hypertrophy. In this study, the ventricular septum thickness was significantly related to age and hypertension. Therefore, we believe that blood pressure and age are synergistically involved in the occurrence and development of left ventricular remodeling.

There is increasing evidence that RA enlargement is an outcome predictor in various cardiac conditions[27]. To date, diameters and areas measured in the apical four-chamber view are the only recommended methods for assessing RA size[28].

RV function is an independent determinant of clinical status and prognosis in a number of pathologies, but its accurate quantification remains a challenge. As compared with LV, the unique features of the RV are its complex geometry, its wider range of loading conditions, and its greater heterogeneity of regional function. RV failure is usually caused by left heart dysfunction. Both conditions coexist[29]. Ventricular interdependence is not only manifested in function, but also in size, which is more obvious in diastole.

5. Limitations

The most obvious limitation of this study was the radiation dose generated by using CT. However, the radiation dose is 3.47 ± 0.68 mSv, which is lower than the radiation protection requirement of X-ray computed tomography. For much lower radiation, scanning voltage and current have been adjusted for body weight and body mass index. And CT is necessary for evaluating coronary artery disease. It can observe not only coronary artery disease but also the heart and make a comprehensive diagnosis of disease. The advantages outweigh the disadvantages for patients with indications, such as coronary heart disease. Moreover, it was a cross-sectional study, and only patients with clear image qualities were evaluated. The free wall of the right ventricle is only 3-5mm, which can be almost ignored. Simultaneously, we adjusted the window width and window level to make the heart cavity more recognizable and easier to measure. Our research requires further follow-up.

6. Conclusion

This study provides applicable quantification cardiac CT cardiac chamber dimensions and LV wall thickness reference ranges in different cardiac phases. Reconstruction and measurement performed in the maximum phase using cardiac CT could result in a more accurate diameter in cardiac disease assessment during the varied cardiac cycle.

Declarations

Funding

Not applicable.

Compliance with ethical standards

Conflict of interest

All authors have nothing to declare.

Ethics approval

This study was conducted in accordance with the the Declaration of Helsinki (as was revised in 2013), and an application for the exemption of patients' informed consent was approved by the Institutional Review Board of our hospital, due to the retrospective nature of the study. So all written informed consent forms are waived.

Authors' contributions

LW and JZ collected data, and were major contributors in writing the manuscript, DC and YD analyzed data, JC provided methods of this study and reviewed the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Consent for publication

Not applicable.

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Figures

Figure 1

Measurement of the cardiac chamber dimension and wall thickness A:LA-A, LA-B were to be traced manually on an image showing the right inferior pulmonary vein insertion (thus avoiding the left auricle), in a plane parallel to the posterior vertebral wall, TVD was measured at the same level. B:RA-A, RA-B, RVD1, RVD2, and RVD3 were measured in the apical four-chamber MPR view. C:The left ventricular wall thickness at the basal, mid and apical segment were measured in the short-axis view of LV. D:LVD1, LVD2, and LVD3 were measured in the long-axis view of LV. (LA-A, left atrial maximum transverse diameter; LA-B, left atrial antero-posterior diameter; TVD, the thoracic vertebral diameter; RA-A, right atrial major dimension; RA-B, right atrial minor dimension; RVD1, right ventricular basal dimension; RVD2, right ventricular mid cavity dimension; RVD3, right ventricular apical-basal dimension; Septum, interventricular septum; Ant, anterior; Ant-Lat, antero-lateral; Post-Lat, infero-lateral; Inf, inferior; LVD1, left ventricular basal dimension; LVD2, left ventricular mid cavity dimension; LVD3, left ventricular apical-basal dimension)

Figure 2

The change trends with cardiac phases of (A)LA and LV, (B) the LV wall thickness of basal, (C)the LV wall thickness of mid, (D)RA and RV. (Abbreviations as in Fig. 1)