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Cardiac Chamber Volumes, Function, and Mass as Determined by 64-Multidetector Row Computed Tomography

Mean Values Among Healthy Adults Free of Hypertension and Obesity

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OBJECTIVES We derived mean values for cardiac dimensions, volumes, function, and mass in a normotensive nonobese population free of cardiovascular disease.

BACKGROUND Multidetector computed tomography (MDCT) permits study of cardiac chamber size, function, and mass. Age- and gender-specific mean values are not available.

METHODS A total of 103 normotensive, nonobese adults (43% women, age 51 ± 14 years) who presented consecutively to 2 medical centers for clinically indicated MDCTs with neither history of nor MDCT evidence of significant cardiovascular disease were studied for left ventricular (LV) and right ventricular (RV) end-systolic (ES) and end-diastolic (ED) linear dimensions and volumes; LV and RV ejection fraction (EF), and LV mass (LVM); and left atrial (LA) and right atrial (RA) end-systolic volumes (LAESV and RAESV, respectively) by 1-dimensional (1D), 2-dimensional (2D), and 3-dimensional (3D) measurements.

RESULTS The LV volumes using 3D techniques were lower than 2D techniques (LVEDV mean 144 ± 71 ml vs. 150 ± 70 ml), with higher LVEF (63 ± 15% vs. 57 ± 13%) ($p < 0.001$ for both). Mean LVM/height$^{2.7}$ was 24.3 ± 11.0 g/m$^{2.7}$ and mean relative wall thickness was 0.16 to 0.44. Evaluation by 20 versus 10 cardiac phases resulted in higher LVEF (mean difference: 3.4 ± 9.0%, $p < 0.001$). For LVEDV, interobserver ($r = 0.99$, $p < 0.001$) and intraobserver ($r^2 = 0.97$, $p < 0.001$) correlations were high. Mean RVEDV was 82 ± 57 ml and RVEF was 58 ± 16. The LAESV determined by 3D techniques was higher than by that determined by 2D methods (102 ± 48 ml vs. 87 ± 57 ml, $p = 0.0003$). The RAESV determined by 3D techniques was 111.9 ± 29.1 ml. The LV size and LVM were greater in men than in women ($p < 0.01$). The LV size declined with age ($p < 0.01$), but LVM did not.

CONCLUSIONS This study establishes age- and gender-specific values for LV, RV, LA, and RA size, function, and mass in adults free of cardiovascular disease, hypertension, and obesity using 1D, 2D, and 3D methods. These data can be used as a reference for future MDCT studies. (J Am Coll Cardiol Img 2008;1:782–6) © 2008 by the American College of Cardiology Foundation

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Multidetector computed tomography (MDCT) is a noninvasive imaging test that permits 3-dimensional (3D) study of cardiac structure and function. To date, reference values have not been established for left ventricular (LV), right ventricular (RV), left atrial (LA), and right atrial (RA) size, function, and mass by MDCT. Age- and gender-specific values are important for classification of disease, stratification of risk, and guidance of therapy.

Reference standards for MDCT cannot be extrapolated from echocardiography or cardiac magnetic resonance imaging (CMR) due to differences in temporal and spatial resolution and signal-to-noise levels (1–3). Prior reports using MDCT for cardiac measures have examined small samples without stratification of age and gender differences and have included individuals with cardiovascular disease (CVD).

We define mean values in normotensive, nonobese individuals free of CVD. We evaluated LV and RV dimensions, end-diastolic and -systolic volumes (EDV and ESV, respectively), ejection fraction (EF), LAESV and RAESV, LV and RV wall thickness (WT), and left ventricular mass (LVM).

METHODS

Population. This study included participants ≥18 years without CVD or hypertension that underwent 64-row cardiac MDCT angiography. Nurses interviewed participants prospectively for CVD, risk factors, and symptoms. Participants were excluded if they had significant CVD, hypertension, or body mass index (BMI) ≥30 kg/m^2. This study was approved by the institutional review boards of Cornell Medical College and the Tennessee Heart Institute.

Cardiac MDCT angiography. Participants underwent MDCT by a standard protocol (4). All scans were performed with 64-row computed tomography scanners (Lightspeed VCT, GE Healthcare, Milwaukee, Wisconsin) using a triple-phase contrast protocol: 60 ml of iodixanol, 50 ml of a 50:50 mix of iodixanol and saline, then 50 ml of saline. Scan parameters were 64 × 0.6 mm collimation, tube voltage 120 mV, 350 to 750 mA. Twenty phases of axial data at 2.5-mm thickness were reconstructed from beginning to end of the cardiac cycle in 5% intervals.

Cardiac chamber measures. Post-processing and interpretation were performed by 2 cardiologists blinded to clinical history. Based on the mid-point of the maximal mitral annular plane to the LV apex in the sagittal view, long- and short-axis planes of the LV and RV were reformatted and assessed for ED and ES phases.

1-DIMENSIONAL (1D) MEASURES. Anteroinferior (AI) and septal-lateral (SL) diameters and WT in short-axis planes were measured at the LV and RV mid-papillary levels at ED and ES. Four-chamber long-axis LV and RV cavity lengths were measured from the apex to the mid-mitral plane in ED and ES. The LVM was estimated using the American Society of Echocardiography equation (2).

2-DIMENSIONAL (2D) MEASURES. We measured LVESV, LVEDV, and LVM using Simpson's method of discs. In a subset (n = 49), ES LA area was measured in 4- and 2-chamber planes and LAESV calculated using the area-length method (2).

3D MEASURES. We obtained 3D volumes for the LV and RV at ED and ES and for the LA and RA at ES using software (CardIQ, Advantage Workstation 4.3, GE Healthcare) that uses a Hounsfield unit–based endocardial border detection technique with manual correction. The LV and RV volumes included the outflow tracts. The LA and RA volumes included appendages.

INTEROBSERVER, INTRAOBSERVER, INTERVENDOR, AND INTERPHASE VARIABILITY. Readers measured the data of 20 participants independently. One reader remeasured the datasets of 20 participants ≥12 weeks after the first measurements. We measured the 3D LVESV, LVEDV, and LVM of 20 participants and of 50 participants with 10 versus 20 phases on 2 workstations (Advantage Workstation, GE Healthcare, and Vitrea Workstation, Vital Images, Minnetonka, Minnesota).

STATISTICS. We estimated a need for 100 patients to obtain a mean value for LV ED dimension to a 95% confidence interval (CI) of 1.5 mm. Means, standard deviations, and 95% CIs were calculated for the overall group, for 3 age groups, and both genders. We compared the 2D and 3D techniques by paired *t* test. Groups were compared using the Student *t* test and analysis of variance. Analyses were performed with SPSS version 12.0 (SPSS Inc., Chicago, Illinois).

ABBREVIATIONS AND ACRONYMS

3D = 3-dimensional
AI = anteroinferior
BMI = body mass index
CMR = cardiac magnetic resonance imaging
CVD = cardiovascular disease
EDV = end-diastolic volume
EF = ejection fraction
ESV = end-systolic volume
LA = left atrium
LV = left ventricle
LVM = left ventricular mass
MDCT = multidetector computed tomography
RA = right atrium
RV = right ventricle
SL = septal-lateral
WT = wall thickness

RESULTS

Participant characteristics. The study population included 103 (59 men) normotensive nonobese par-

Table 1. Mean LV Dimensions, Function, and Mass

LV Dimensions and Function	Mean (SD)	95% CI	LVM	Mean (SD)	95% CI
1D					
LVIDd, septal-lateral	47.4 (4.7)	38.2–56.6	Average wall thickness, mm	7.3 (1.3)	4.8–9.8
LVIDd, anteroinferior	57.7 (5.5)	46.9–68.5	Relative wall thickness, %	0.30 (0.07)	0.16–0.44
LV apical-annular length, ED	87.6 (9.3)	69.4–105.8	ASE estimated LVM, g	132.2 (38.5)	56.7–207.7
2D			ASE estimated LVMI, g/m^2	69.7 (16.9)	36.6–102.8
LVESV, ml	65.2 (20.9)	24.2–106.2	ASE LVM/Ht$^{2.7}$, g/m$^{2.7}$	30.2 (7.6)	15.3–45.1
LVEDV, ml	150.4 (35.6)	80.6–220.2	2D LVM ED, g	106.7 (30.1)	47.7–165.7
LVEDVI, ml/m^2	79.5 (15.1)	49.9–109.1	2D LVMI ED, g/m^2	56.2 (12.7)	31.3–81.1
LVEF, %	57.2 (6.8)	43.9–70.5	2D LVM/Ht$^{2.7}$, g/m$^{2.7}$	24.3 (11.0)	13.3–35.3
3D			2D LVM ED papillary free, g	114.8 (30.9)	54.2–175.4
LVESV, ml	52.6 (19.2)	15.0–90.2			
LVEDV, ml	143.6 (36.4)	72.3–214.9			
LVEDVI, ml/m^2	75.8 (15.0)	46.4–105.2			
LVEF, %	63.8 (7.7)	48.7–78.9			

ASE = American Society of Echocardiography; ED = end-diastole; Ht = height; LV = left ventricle; LVEDV = left ventricle end-diastolic volume; LVEDVI = left ventricle end-diastolic volume index; LVEF = left ventricular ejection fraction; LVESV = left ventricle end-systolic volume; LVIDd = left ventricular internal dimension end-diastole; LVM = left ventricular mass; LVMI = left ventricular mass index; 1D = 1-dimensional; 2D = 2-dimensional; 3D = 3-dimensional.

ticipants without CVD. The mean age was 51.1 ± 13.6 years, with a mean BMI of 25.0 ± 2.9 kg/m^2. Of the population, 2% had diabetes and 37% had dyslipidemia, with 47% smokers; 72% were Caucasian, 10% were Asian, 7% Hispanic, 3% African American, and 7% other ethnicities. All patients were in sinus rhythm. The average coronary artery calcium score was 32.3 ± 71.9.

LV cavity measures. The LV measures are shown in Table 1. Short-axis specifications resulted in a noncircular geometry of the LV, with longer AI compared with SL measurements ($p < 0.001$ for base and mid-cavitary diameters in ED and ES). Basal AI ED and ES dimension 95% CI were 44 to 67 mm and 23 to 44 mm, respectively. Basal SL ED and ES 95% CI were 38 to 58 mm and 25 to 46 mm.

The 2D LVEDV and LVESV 95% CI were 81 to 220 ml and 24 to 106 ml, respectively. The 3D LVEDV and LVESV 95% CI were 72 to 215 ml and 15 to 90 ml, respectively. Histograms for LV measures are shown in Figure 1.

LV function. The 3D measures were highly correlated ($r^2 = 0.99$, $p < 0.001$) but lower than 2D measures (Table 1). The 3D LVEF was higher than 2D LVEF. In a subset (n = 56), differences

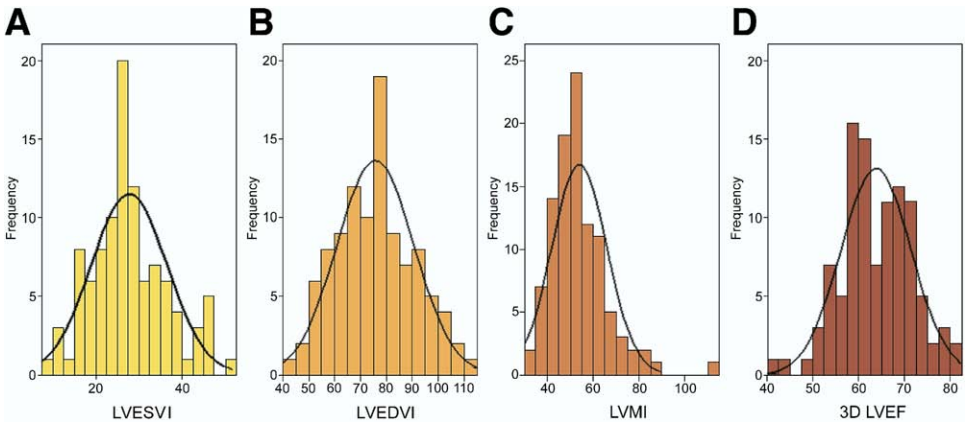

Figure 1. Histograms of LVESVI, LVEDVI, LVMI, and 3D LVEF

Tabulations of frequencies of left ventricular end-systolic volume (**A**), end-diastolic volume (**B**), mass indexed to body surface area (**C**), as well as 3-dimensional ranges for left ventricular ejection fraction (**D**), revealed an overall bell-shaped distribution for all measures of left ventricular volumes, mass, and function. LVEDVI = left ventricular end-diastolic volume index; LVEF = left ventricular ejection fraction; LVESVI = left ventricular end-systolic volume index; LVMI = left ventricular mass index; 3D = 3-dimensional.

Table 2. Mean RV Dimensions, Volumes, and Function

	End-Systolic		End-Diastolic				
RV Dimensions	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**	**Other RV Measures**	**Mean (SD)**	**95% CI**
Linear (n = 103)					Remodeling		
Mid-cavity, septal-medial, mm	29.6 (5.3)	19.2–40.0	37.0 (5.7)	25.8–48.2	RV free wall thickness	2.4 (0.7)	1.0–3.8
Mid-cavity, anterior-inferior, mm	57.9 (8.0)	42.2–73.6	72.6 (9.0)	55.0–90.2			
Apical-annular length, mm	62.0 (8.8)	44.8–79.2	77.7 (10.4)	57.3–98.1			
3D (n = 85)					Functional measures		
3D volume, ml	82.1 (29.2)	24.9–139.3	174.9 (48.0)	80.8–269.0	Tricuspid annular excursion, mm	29.6 (5.3)	19.2–40.0
3D volume index, ml/m^2			93.3 (20.3)	53.5–133.1	3D RVEF, %	57.9 (8.0)	42.2–73.6

RV = right ventricle; RVEF = right ventricular ejection fraction; other abbreviations as in Table 1.

between papillary-free 2D and 3D measures were significant, but smaller in magnitude than those obtained from papillary-inclusive 2D measures (ESVΔ: 2.8 ± 13.0 ml, EDVΔ: 7.5 ± 29.0; $p < 0.01$ for both). The 3D LVEF was not different from the 2D papillary-free measures (p = NS).

Interobserver and interphase variability. In a subset of 20 patients, interobserver agreement of 3D volumes was high ($r^2 = 0.99$ for LVEDV and LVESV, $p < 0.001$ for both). Intraobserver agreement was also high ($r^2 = 0.98$ and 0.97 for LVEDV and LVESV, respectively, $p < 0.001$ for both). Similarly, LV measures using 2 workstations demonstrated excellent agreement ($r^2 = 0.94$, 0.96 and 0.93 for LVEDV, LVESV, and LVM, respectively, $p < 0.001$ for all).

For interphase variability, we measured 3D volumes in a subset (n = 55) using 20 versus 10 phases. There was no difference for ESV, but mean EDV was higher using 20 versus 10 phases (9 ± 21 ml, $p < 0.001$), thus underestimating LVEF using 10 rather than 20 phases (3 ± 9%, $p < 0.001$).

LV and RV WT and mass. The LV WT 95% CI was 4.8 to 9.8 mm, with no difference between different LV walls (p = NS). The RWT 95% CI was 0.16 to 0.44 (Table 1). The 95% CI for LVM/height$^{2.7}$ was 13.3 to 35.3 g/m$^{2.7}$.

RV measures. The RV ED SL and AI 95% CI were 26 to 48 mm and 55 to 90 mm, respectively (Table 2). Tricuspid annular excursion in a subset (n = 62) was 19 to 40 mm. The RV WT was 1.0 to 3.8 mm. We were unable to evaluate 17% (n = 18) of the RA and RV due to insufficient right-sided contrast. The 3D RVEDV and RVESV were 81 to 269 ml and 25 to 139 ml, respectively, with RVEF of 42% to 74%.

LA and RA measures. The LAESV was 55 to 150 ml (Table 3). Calculated LAESVs were lower at 30 to 144 ml (mean difference compared with 3D LAESV: 13 ± 47 ml, p = 0.003). The 3D RAESV was 30 to 89 ml.

Mean values by age, sex and BMI. Measured LV volumes declined with age (p = 0.001 for LVEDV using 1D, 2D, and 3D techniques) even after indexation to body surface area. Small increases in LVEF with age were seen by 3D ($p < 0.05$), but not 2D measurements. No association of LVM with age was seen. The 3D LVEDVI and LVEF 95% CI were 49.4 to 115.2 ml and 50.2 to 71.8 ml, 49.4 to 100.8 ml and 48.9 to 78.7 ml, and 38.0 to 100.0 ml and 49.4 to 86.2 ml for ages <40, 40 to 65, and >65 years, respectively. The 2D and 3D LVEDV was higher in men than in women, even after indexation for body surface area (all $p < 0.001$). No gender differences were observed for LVEF by 2D or 3D techniques (p = NS for all). The LVM was higher in men, even after indexation for height$^{2.7}$ ($p < 0.05$ for all). The 3D LVEDVI and 2D LVM/Ht$^{2.7}$ 95% CI were 43.0 to 99.0 ml and 13.7 to 32.6 g/m$^{2.7}$, and 50.6 to 108.2 ml and 13.8 to 37.3 g/m$^{2.7}$ for women and men, respectively.

The LV volumes and LVEF were not associated with BMI. The LVM was higher for BMI ≥25

Table 3. LA and RA Volumes

	2D LAESV (n = 49)		3D LAESV (n = 103)		3D RAESV (n = 85)	
Atrial Dimensions	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**
Volume, ml	86.5 (29.1)	29.5–143.5	102.3 (24.4)	54.5–150.1	111.9 (29.1)	54.9–168.9
Volume index, ml/m^2	46.2 (13.9)	19.0–73.4	54.4 (11.9)	31.1–77.7	59.7 (15.0)	30.3–89.1

LA = left atrium; LAESV = left atrial end-systolic volume; RA = right atrium; RAESV = right atrial end-systolic volume; other abbreviations as in Table 1.

kg/m^2 versus BMI <25 kg/m^2, even after indexation for body surface area and height$^{2.7}$ ($p < 0.001$).

DISCUSSION

We established mean values and 95% CIs for LA, RA, LV, and RV size; function; and mass by 64-row MDCT in normotensive, nonobese adults without CVD. The LV measures by 2D and 3D exhibited significant variation by body size, age, and gender. Thus, we examined LV mean values and 95% CIs with indexation for body size by age and gender.

The LV measures by MDCT compare favorably to CMR, the standard for assessment of LV function. A meta-analysis found no differences between MDCT and CMR for LVEDV, LVEF, or LVM (1). Several studies have assessed MDCT to quantify LV and RV function but have not established mean values due to small samples, inclusion of patients with CVD, and use of older generation scanners. Normal LA and RA volumes have not been assessed by MDCT.

Our measurements are similar to prior observations by CMR (2). Underestimation of LAESV by echocardiogram using the Simpson rule and area-length volume formulas has been observed by both computed tomography and CMR (5). Small differences in LV and RV measurements from norms by MDCT compared with CMR or echocardiogram may be due to papillary muscle exclusion by MDCT and differences in spatial and temporal resolution. Prior studies examining the number of reconstructed phases have found lower LVEF using 10 versus 20 phases, and 10-phase MDCT underestimates LVEF compared with CMR and 3D echocardiogram (3). We also observed LVEF underestimation with 10 phases.

We found differences in LV volumes and mass by age, gender, and BMI. Prior CMR studies suggest that age- and gender-specific values accounting for body size should be used to assess cardiac size and function; our results confirm this notion (2).

Study limitations. No comparative imaging modality was used. Numerous studies have examined LV and RV by MDCT, demonstrating excellent correlation to CMR and echocardiogram (1). Our study examined cardiac measurements in a cohort of healthy participants to develop mean reference values.

This study was not a population study. MDCT uses ionizing radiation and contrast and is inappropriate for population studies. Nevertheless, the meticulous nature by which we defined and identified healthy individuals without CVD permitted study of participants spanning a wide age range that is similar to population-based studies.

CONCLUSIONS

The current data establish mean values for LV, RV, LA, and RA size; function; and mass MDCT using 1D, 2D, and 3D methods. This study found differences among 1D, 2D, and 3D methods, as well as for age and gender. These data can be used as a reference for future MDCT studies.

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Key Words: left ventricle ■ left ventricular mass ■ left ventricular volume ■ computed tomography ■ left ventricular function.