Journal of the American College of Cardiology
© 2012 by the American College of Cardiology Foundation
Published by Elsevier Inc.

Vol. 59, No. 21, 2012
ISSN 0735-1097/$36.00
doi:10.1016/j.jacc.2012.01.046

Cardiac Imaging

Head-to-Head Comparison of Left Ventricular Function Assessment with 64-Row Computed Tomography, Biplane Left Cineventriculography, and Both 2- and 3-Dimensional Transthoracic Echocardiography

Comparison With Magnetic Resonance Imaging as the Reference Standard

Johannes Greupner, MD,* Elke Zimmermann, MD,* Andrea Grohmann, MD,† Hans-Peter Dübel, MD, PHD,† Till Althoff, MD,† Adrian C. Borges, MD, PHD,† Wolfgang Rutsch, MD, PHD,† Peter Schlattmann, PHD,‡ Bernd Hamm, MD, PHD,* Marc Dewey, MD, PHD*

Berlin and Jena, Germany

Objectives This study was designed to compare the accuracy of 64-row contrast computed tomography (CT), invasive cineventriculography (CVG), 2-dimensional echocardiography (2D Echo), and 3-dimensional echocardiography (3D Echo) for left ventricular (LV) function assessment with magnetic resonance imaging (MRI).

Background Cardiac function is an important determinant of therapy and is a major predictor for long-term survival in patients with coronary artery disease. A number of methods are available for assessment of function, but there are limited data on the comparison between these multiple methods in the same patients.

Methods A total of 36 patients prospectively underwent 64-row CT, CVG, 2D Echo, 3D Echo, and MRI (as the reference standard). Global and regional LV wall motion and ejection fraction (EF) were measured. In addition, assessment of interobserver agreement was performed.

Results For the global EF, Bland-Altman analysis showed significantly higher agreement between CT and MRI ($p < 0.005$, 95% confidence interval: ±14.2%) than for CVG (±20.2%) and 3D Echo (±21.2%). Only CVG (59.5 ± 13.9%, $p = 0.03$) significantly overestimated EF in comparison with MRI (55.6 ± 16.0%). CT showed significantly better agreement for stroke volume than 2D Echo, 3D Echo, and CVG. In comparison with MRI, CVG—but not CT—significantly overestimated the end-diastolic volume ($p < 0.001$), whereas 2D Echo and 3D Echo significantly underestimated the EDV ($p < 0.05$). There was no significant difference in diagnostic accuracy (range: 76% to 88%) for regional LV function assessment between the 4 methods when compared with MRI. Interobserver agreement for EF showed high intraclass correlation for 64-row CT, MRI, 2D Echo, and 3D Echo (intraclass correlation coefficient >0.8), whereas agreement was lower for CVG (intraclass correlation coefficient = 0.58).

Conclusions 64-row CT may be more accurate than CVG, 2D Echo, and 3D Echo in comparison with MRI as the reference standard for assessment of global LV function. (J Am Coll Cardiol 2012;59:1897–907) © 2012 by the American College of Cardiology Foundation

From the *Department of Radiology, Charité Medical School, Berlin, Germany; †Department of Cardiology, Charité Medical School, Berlin, Germany; and the ‡Department of Medical Statistics, Informatics and Documentation (PS), University Hospital of Friedrich-Schiller University Jena, Jena, Germany. Dr. Dübel is deceased. Dr. Dewey has received grant support from GE Healthcare Biosciences, Bracco, Guerbet, and Toshiba Medical Systems; has received lecture fees from Toshiba Medical Systems and Bayer (Schering-Berlex); is a principal investigator of multicenter studies on cardiac computed tomography (CORE-64 and CORE-320) sponsored by Toshiba Medical Systems; is the author of Coronary CT Angiography and Cardiac CT, published by Springer, and offers hands-on workshops on cardiac CT (www.ct-kurs.de); is a consultant for Guerbet; is a speaker for Toshiba Medical Systems, Cardiac MR Academy Berlin, Guerbet, and Bayer-Schering; and has relationships with the German Heart Foundation and the European Fund for Regional Development. Dr. Hamm has received grant support from GE Healthcare, Schering, Siemens Medical Solutions, and Toshiba Medical Systems; and has received lecture fees from Siemens Medical Solutions and Schering. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

Manuscript received June 28, 2011; revised manuscript received December 27, 2011, accepted January 17, 2012.

Abbreviations and Acronyms

2D Echo = 2-dimensional echocardiography

3D Echo = 3-dimensional echocardiography

CT = computed tomography

CVG = cineventriculography

EDV = end-diastolic volume

EF = ejection fraction

ESV = end-systolic volume

LV = left ventricular

MRI = magnetic resonance imaging

SV = stroke volume

Left ventricular (LV) function is an important factor in terms of patient management, outcome, and long-term survival of patients with cardiac disease (1,2). Several diagnostic methods are available to evaluate LV function, among which 2-dimensional echocardiography (2D Echo) is the most widely used because it offers fast, relatively inexpensive, and noninvasive functional analysis without radiation exposure or contrast medium administration. Nevertheless, 2D Echo has several limitations, including operator dependence, variable acoustic windows, and inadequate endocardial border discrimination (3,4). Furthermore, it depends on the use of geometric assumptions (5). Three-dimensional echocardiography (3D Echo) overcomes these limitations by capturing entire volumes, which is of great importance in deformed ventricles (6–8). Another option is biplane cineventriculography (CVG) as part of cardiac catheterization, whose invasive nature has important drawbacks. Additionally, being a projectional method, CVG is limited by similar geometric assumptions as 2D Echo. Magnetic resonance imaging (MRI) is considered the method of choice for global and regional myocardial function assessment (9).

In recent multicenter studies, 64-row computed tomography (CT) was proven to be reliable and accurate in noninvasively assessing the coronary arteries (10–12). Moreover, CT also enables assessment of LV function (13–15). Although it has been shown that coronary CT angiography has become more reliable with the increasing detector rows to 64-row scanners (12,16), it remains unclear if these scanners also allow improved LV function assessment. We therefore performed an intraindividual comparative effectiveness assessment of all 5 tests (64-row CT, 2D Echo, 3D Echo, and CVG, with MRI as the reference) for evaluation of global and regional LV function (Fig. 1).

Methods

Study design. This prospective diagnostic performance study was carried out as an ancillary single-center study of the CorE 64 multicenter trial (11,17) to evaluate 64-row CT, 2D Echo, 3D Echo, and CVG for the assessment of global and regional LV function, using MRI as the reference standard. An intention-to-diagnose design was used; no patients or segments were excluded because of poor image quality, but instead were considered nondiagnostic. The locations of the 25 criteria of the Standards for Reporting of Diagnostic Accuracy studies statement (18) in this report are summarized in Online Table 1. All patients underwent all 5 tests within 24 h to minimize changes in cardiac function. The study protocol was approved by the institutional review board, and written informed consent was obtained from all patients.

Study group. The study group consisted of consecutive patients who had a clinical indication for conventional coronary angiography and were referred to Charité Medical School for coronary catheterization. Inclusion criteria for this study were sinus rhythm and an age of at least 40 years (17). Patients with a known allergy to iodinated contrast agent, contraindication to beta-blockers or nitroglycerin,

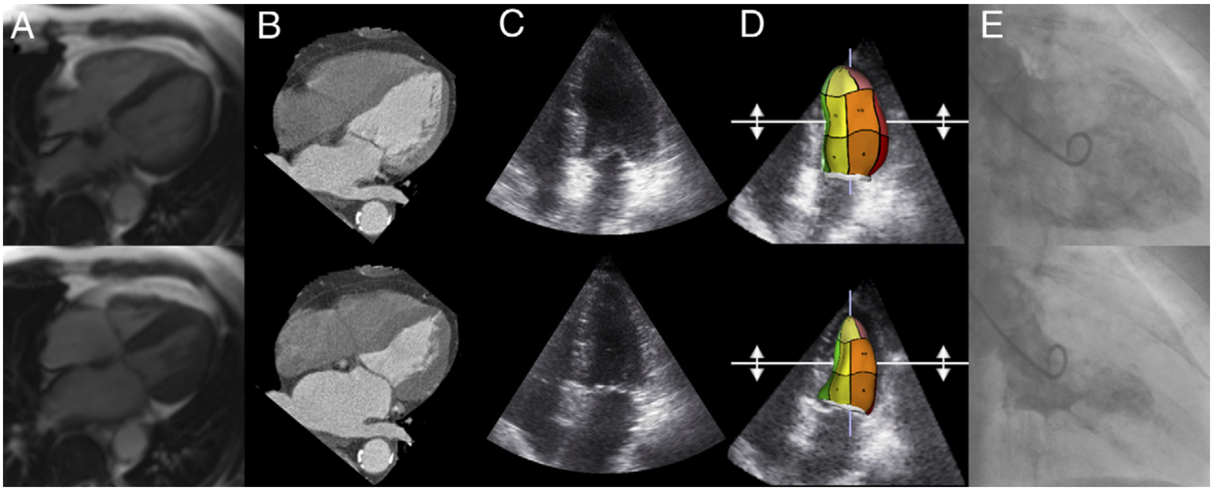

Figure 1 **Normal Left Ventricular Function in an 82-Year-Old Woman**

(Top row) Diastole and **(bottom row)** systole studied by **(A)** magnetic resonance imaging, **(B)** 64-row computed tomography, **(C)** 2-dimensional echocardiography, **(D)** 3-dimensional echocardiography, **(E)** cineventriculography.

Table 1 Patient Characteristics

Age, yrs	62.2 ± 11.2
Male	31 (86)
Hyperlipoproteinemia	23 (64)
Diabetes mellitus	7 (19)
Hypertension	24 (67)
Smokers	7 (19)
BMI >25 kg/m^2	7 (19)
Known coronary artery disease	11 (31)
Previous myocardial infarction	6 (17)

Values are mean ± SD or n (%).
BMI = body mass index.

who were pregnant, who had renal insufficiency (creatinine clearance of <60 ml/min or serum creatinine of more than 1.5 mg/dl), who had coronary bypass grafts, who had undergone coronary intervention within 6 months before study enrollment as pre-specified (17), or who had known contraindications to MRI (e.g., pacemaker) were excluded. In addition, women of childbearing age had a pregnancy test before enrollment. Enrollment took place between August 8, 2006, and January 31, 2007 (excluding holidays and weekends).

MRI acquisition protocol and data analysis. MRI was performed on a 1.5-T scanner (Magnetom Avanto, Siemens AG, Erlangen, Germany). For cardiac synchronization and patient monitoring, an active 3-lead electrocardiography system was used. Cine MRI scans were acquired in the 2-, 3-, and 4-chamber view and short-axis orientations during end-expiratory breath-hold using a segmented fast steady-state free precession sequence, as recently described (19). Imaging parameters were repetition time: 2.8 ms, echo time: 1.2 ms, slice thickness: 8 mm, no interslice gap, voxel size: 1.7 × 1.3 × 8 mm^3, acquisition window/cardiac phase: 34 ms (24 segments per phase), slice resolution: 100%, and flip angle: 54° (20,21). Parallel imaging with a factor of 2 was used, and 2 slices along the short-axis orientations were acquired during a single breath-hold covering the entire heart from base to apex without gaps.

Analysis of global LV function was performed on a commercially available workstation (ARGUS version VA60c, Siemens) using Simpson's rule for calculating end-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV), ejection fraction (EF), and myocardial mass. For this, epicardial and endocardial borders were marked on each slice, the luminal area then was multiplied by the slice thickness, and the volumes of the slices finally were added. Basal slices with less than a semicircular muscular ring at end systole were disregarded, papillary muscles were assigned to the LV muscle (22), and the LV outflow tract was not included. End-systole and end-diastole then were detected automatically by the software according to the smallest and largest ventricular volume.

64-row CT acquisition protocol, image reconstruction, and data analysis. Images were acquired during a single submaximum inspiratory breath-hold on a 64-row CT-scanner (Aquilion 64, Toshiba, Otawara, Japan) using 64 × 0.5-mm collimation. The examination was carried out using a tube voltage of 120 kV, a tube current of 240 to 400 mA (according to patient body weight and sex), pitch of 0.2 to 0.225 (according to heart rate), and a gantry rotation time of 400 ms (17). The effective dose was estimated using CT-Expo (23). Parallel to the scan, an electrocardiogram was recorded digitally to allow retrospective gating. If a patient's heart rate exceeded 70 beats/min, a beta-blocker (atenolol) was administered 1 h before the examination. When this approach did not result in adequate heart rate lowering, a short-lasting beta-blocker (esmolol) was administered intravenously immediately before the examination on the scanning table. In addition, all patients also received 1.2 mg nitroglycerin sublingually immediately before the scan, which was optimized for coronary CT angiography, to increase coronary artery diameters (24). A total of 80 to 100 ml, depending on the patient's body weight, of a nonionic contrast agent (iopamidol 370, Bracco, Konstanz, Germany) was injected into a cubical vein at a flow rate of 3.5 to 5 ml/s, followed by a saline chaser bolus of 40 ml at a flow of 3 ml/s. The automatic bolus-tracking feature of the scanner was used to start image acquisition when a threshold of 180 HU in the descending aorta was reached (17).

From the raw data of each scan, axial image series with 0.5-mm slice thickness and an increment of 0.5 mm were reconstructed by means of adaptive multisegment (multicycle) reconstruction using data from up to 4 consecutive heart beats for the same phase at 10 time points in 10% intervals of the cardiac cycles, as recently described (19). These 0.5-mm images were used to assess function with the scanner's en suite software (Aquilion 64 version 3.00, Toshiba, Otawara, Japan). Short-axis slices of 8 mm width without interslice gap were generated. The software's semiautomatic endocardial and epicardial border detection tool was used on each short-axis slice, adjusting them manually if necessary, as described recently (25). Similar to MRI, papillary muscles also were assigned to the LV muscle (22), and basal slices with less than a 180° circumferential LV muscle ring during end-systole were disregarded as recommended (26). The LV outflow tract was not included. Simpson's rule was used to calculate LV volumes. Subsequently, end-systolic and end-diastolic phases were detected automatically by the software according to the smallest and largest ventricular volume, similar to MRI.

CVG data acquisition and data analysis. All patients underwent biplane CVG using standard x-ray techniques during end-expiratory breath hold with a frame rate of 30/s and injecting 30-ml iodated contrast media at a flow rate of 10 to 12 ml/s using a 5- or 7-F pigtail catheter.

LV function was analyzed in 2 orthogonal planes (30° right anterior oblique and 60° left anterior oblique) using a commercially available workstation (Med Con, Tel Aviv, Israel). Ventricular borders were traced automatically by border detection software that could be adjusted manually. Consequently, absolute cardiac function values were calcu-

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lated using the area-length method and metallic spheres for calibration (27,28). For comparison of effective radiation dose of catheterization (including angiography and CVG), we used dose area product measurements with a conversion factor (0.2 mSv/cGy · cm), including only radiation associated with the diagnostic coronary angiogram and CVG (29).

2D Echo and 3D Echo acquisition protocol and data analysis. All patients underwent 2D Echo as well as 3D Echo. 2D Echo was performed at a frame rate of 40 to 80 frames/s in the left lateral decubitus position to obtain standard 2-, 3-, and 4-chamber as well as short-axis views (GE Vingmed Vivid 7 Dimension, Horton, Norway; 2.5-MHz transducer). Manual tracing of the endocardial borders at end systole and end diastole was performed, and the modified biplane Simpson's rule was used to calculate end-systolic and end-diastolic volumes (30). After 2D Echo, the machine's 1.5- to 3.6-MHz 3V transducer (GE Vingmed Vivid 7 dimension) was used to obtain 3D pyramidal datasets (sector angle: 80° × 82°) at a frame rate of 39 frames/s during an end-expiratory breath hold lasting up to 6 heart beats. All acquired real-time 3D datasets then were transferred to a dedicated workstation (TomTec 4D, TomTec Imaging Systems GmbH, München, Germany), and LV volumes were calculated semiautomatically (31).

Assessment of regional function and experience level of the reader. For regional LV function assessment (Fig. 2), we rated all 17 myocardial segments (32) using a 4-point scale (1 = normal, 2 = hypokinesia, 3 = akinesia, 4 = dyskinesia). All assessments (both global and regional assessments) were performed by 2 readers who were blinded to each other and to the results of the other tests. The readers had the following levels of experience: MRI, 3 and 8 years (E.Z., B.H.); 64-row CT, 4 and 8 years (J.G., M.D.); echocardiography, 5 and 15 years (A.G., A.C.B.); and CVG, more than 20 years each (W.R., H.P.D.).

Image quality. Overall image quality was assessed on a 5-point scale for all 5 tests: 1 = nondiagnostic; 2 = poor; 3 = average; 4 = good; 5 = very good.

Statistical analysis. All data are expressed as mean ± SD unless otherwise stated. According to the intention-to-diagnose design of the study, no patient or segment was excluded because of poor image quality, but instead was considered nondiagnostic. For intermethod analysis, the results of the most experienced reader of each method were used. LV cardiac function parameters of 64-row CT, CVG, 2D Echo, and 3D Echo were compared with MRI as the reference standard using Pearson's correlation and limits of agreement (1.96 × SD = 95% confidence intervals) determined by Bland-Altman analysis (33). A paired Student *t* test was used to test for any overestimation or underestimation, and a 2-tailed F test was used to compare the size of the limits of agreement of 64-row CT, CVG, 2D Echo, and 3D Echo in reference to MRI in the Bland-Altman analysis. Furthermore, we used the methods described above to compare 64-row CT with MRI regarding myocardial mass.

In addition, for assessment of sensitivity, specificity, and positive and negative predictive value for abnormal regional cardiac function (grades 2 to 4), the results of MRI served as reference for evaluation of 64-row CT, CVG, 2D Echo, and 3D Echo. We used a McNemar test to compare the diagnostic performance for detection of regional wall motion abnormality on the per-patient and per-segment level between 64-row CT, CVG, 2D Echo, and 3D Echo. Accuracy in differentiation of wall motion deficits on the 4-point scale for CT, CVG, 2D Echo, and 3D Echo was compared with MRI as the reference standard using a paired

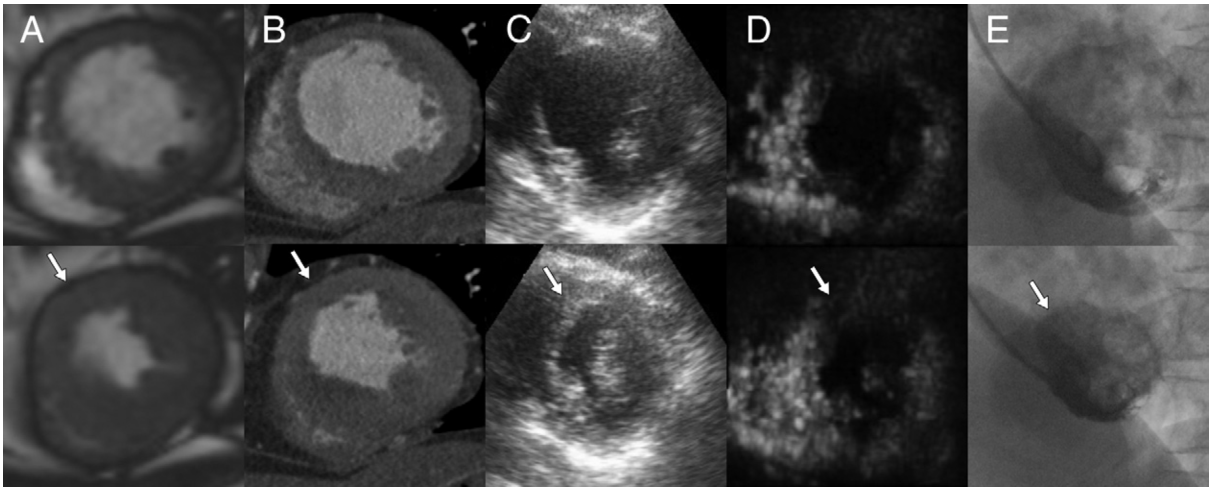

Figure 2 **Abnormal Regional Function in a 53-Year-Old Man**

(Top row) Diastole and **(bottom row)** systole studied by **(A)** magnetic resonance imaging, **(B)** 64-row computed tomography, **(C)** 2-dimensional echocardiography, **(D)** 3-dimensional echocardiography, **(E)** cineventriculography. During systole, all tests show hypokinesis **(arrow)** of the anteroseptal myocardial segment (segment 7). Note also the thinning of the septal wall **(A to C)** and the darkening of the subendocardial border in this area **(A, B)**, which are the result of prior ischemic damage.

McNemar test and Cohen's kappa statistic on the per-segment level. We used Bland-Altman analysis as well as intraclass correlation analysis for global function assessment and Cohen's kappa for regional function assessment. Furthermore, we used Friedman's test to compare image quality. Statistical analysis was conducted using SPSS software version 12.0 (SPSS, Inc., Chicago, Illinois). A p value <0.05 was considered significant.

Results

During the enrollment period, 83 patients were eligible, of whom 7 eligible patients were not in sinus rhythm, 3 and 4 had contraindications to iodinated contrast agents and beta-blockers, respectively, 4 had coronary artery bypass grafts or coronary interventions within 6 months before study enrollment, and 2 had cardiac pacemakers. Another 6 patients were already recruited into other trials. Of the remaining 57 eligible patients, 14 declined to participate and 7 had to be excluded because of time constraints and unavailability of at least 1 of the 5 tests during the 24 h period. Thus, 36 patients (Table 1) with suspected (n = 26) or known (n = 10) coronary disease successfully completed the study and underwent the 5 diagnostic tests within 24 h without any complications or intermediate cardiac events.

For 64-row CT, on average 81.1 ± 4.6 ml contrast agent was administered intravenously, and the effective dose was 16.2 ± 1.7 mSv (23). The average heart rate during CT was 58.7 ± 8.7 beats/min, and the average length of the image reconstruction window was 179.0 ± 14.8 ms. Thirteen patients required intravenous beta-blockade (esmolol 245 ± 145 mg) and 1 patient received an additional oral beta-blocker (50 mg atenolol). For diagnostic cardiac catheterization, the total effective dose was 13.8 ± 6.8 mSv and 86.5 ± 31.2 ml (including 30 ml for CVG) of contrast agent used (both $p > 0.05$ vs. CT).

Overall EF measured by MRI was 55.6 ± 16.0% (range: 12.6% to 74.6%), and one third of the patients (12 of 36) showed reduced EF (<55%).

Image quality. Overall image quality was not significantly different ($p = 0.22$ for all) between 64-row CT (3.0 ± 0.8), 2D Echo (3.2 ± 0.9), 3D Echo (3.0 ± 1.0), CVG (3.3 ± 0.7), and MRI (3.6 ± 0.9). None of the examinations was deemed nondiagnostic by the respective readers.

LV EF. There was no significant overestimation or underestimation by 64-row CT, 2D Echo, or 3D Echo in comparison with MRI (Fig. 3A), but CVG significantly overestimated EF ($p = 0.03$, *t* test) (Table 2). Compared with the limits of agreement for 64-row CT versus MRI (±14.2%), CVG (±20.2%, $p = 0.02$) and 3D Echo (±21.2%, $p = 0.01$) showed significantly larger variability. Furthermore, 64-row CT (Fig. 3B) showed an excellent correlation with MRI for EF (Table 2). There was good correlation for 2D Echo and 3D Echo as well as for CVG (Table 3). 64-row CT showed high intraclass correlation with MRI, whereas CVG, 2D Echo, and 3D Echo showed good intraclass correlation (Online Table 2).

LV EDV. For EDV, 64-row CT showed no significant overestimation or underestimation ($p = 0.63$), whereas both 2D Echo ($p < 0.001$) and 3D Echo ($p = 0.004$) significantly underestimated this LV function parameter, and CVG ($p = 0.01$) overestimated this LV function parameter (Table 2). Bland-Altman analysis demonstrated no significant difference ($p > 0.05$ for all) for the limits of agreement for 2D Echo, 3D Echo, and CVG in comparison with 64-row CT (Fig. 3C). Again, there was good correlation between 64-row CT, 2D Echo, 3D Echo, and CVG compared with MRI (Table 3). There was high intraclass correlation for all 5 tests (Online Table 2).

LV ESV. Similar to EDV, there was no significant overestimation or underestimation of ESV by 64-row CT ($p = 0.998$), but 2D Echo ($p = 0.002$) and 3D Echo ($p = 0.005$) significantly underestimated this LV function parameter, and CVG ($p = 0.001$) overestimated this LV function parameter (Table 2). Again, there were no significant differences in the limits of agreement for any of the tests (Fig. 3D). Correlation analysis showed an excellent correlation for 64-row CT, 2D Echo, 3D Echo, and CVG with MRI (Table 3). Again, there was high intraclass correlation for all 5 tests (Online Table 2).

LV SV. SV was overestimated significantly by both 64-row CT ($p = 0.02$) and CVG ($p < 0.001$) (Table 2). In contrast, 2D Echo ($p = 0.01$) significantly underestimated SV, whereas 3D Echo showed no significant overestimation or underestimation of SV (Table 2). Bland-Altman analysis revealed significantly larger limits of agreement ($p < 0.05$ for all) for CVG as well as for 2D Echo and 3D Echo than for 64-row CT (Fig. 3B). Correlation with MRI was moderate for 64-row CT and was low for CVG, 2D Echo, and 3D Echo (Table 3). For SV, 64-row CT showed moderate intraclass correlation, whereas CVG, 2D Echo, and 3D Echo showed only fair agreement (Online Table 2).

LV myocardial mass. 64-row CT resulted in limits of agreement versus MRI of ±42.0 g, with an excellent correlation between both tests (Table 3).

Per-patient regional function. Using MRI as the reference standard, 22 of 36 patients were classified as having at least 1 myocardial segment with a wall motion deficit (Fig. 2). Of these 22 patients, 7 patients also showed akinetic wall segments, and 1 patient also showed dyskinetic wall segments.

64-row CT showed a significantly higher sensitivity than both 2D Echo and 3D Echo ($p < 0.05$ for both) (Table 4). By contrast, 64-row CT showed a significantly lower specificity than both 2D Echo and 3D Echo ($p < 0.05$ for both) (Table 4). See Online Tables 3 through 6 for cross-tables for all tests versus MRI.

Per-segment regional function. The reference standard, MRI, identified 154 segments with a wall motion deficit (a score of at least 2: hypokinetic, n = 102; akinetic, n = 47; dyskinetic, n = 5), and sensitivity of 64-row CT was

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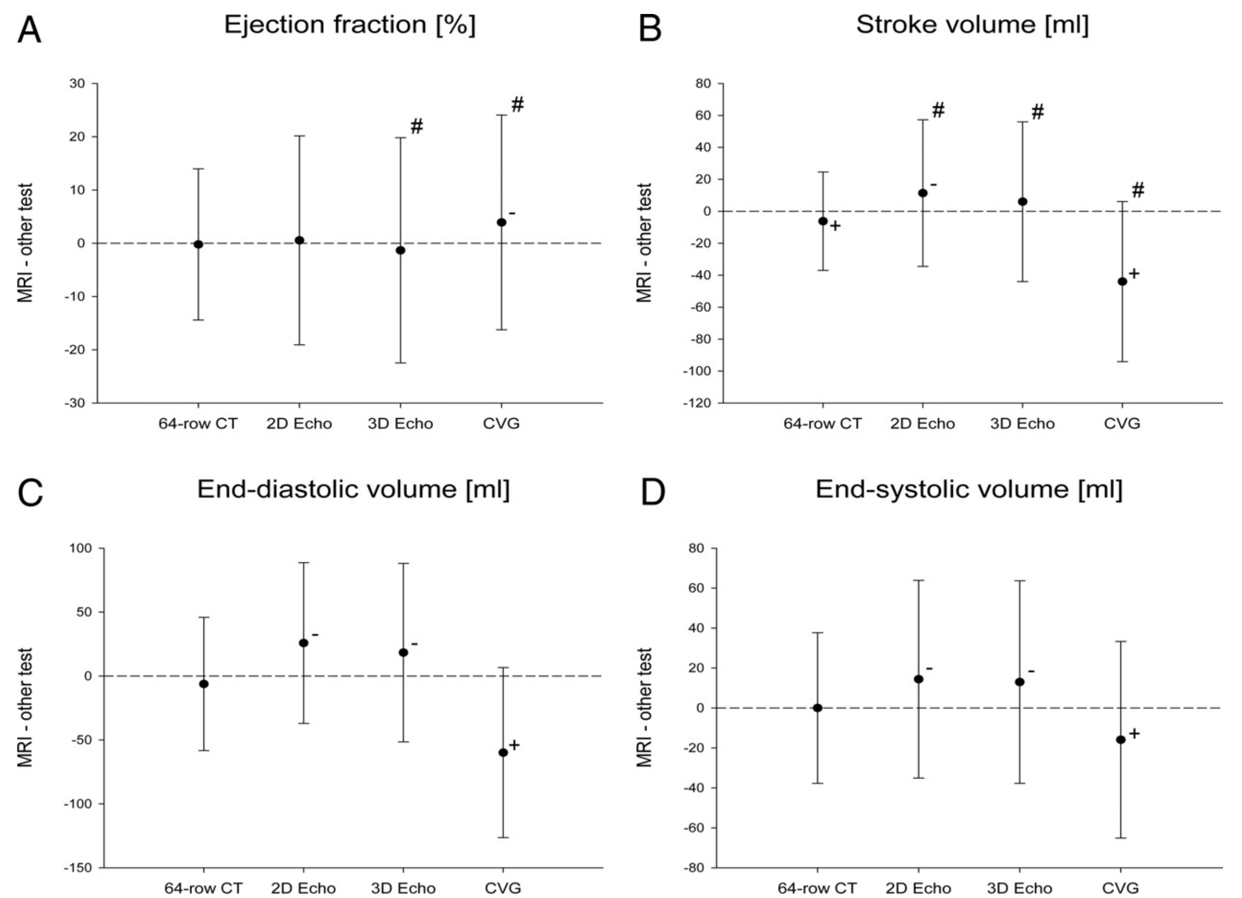

Figure 3 **Summary of the Bland-Altman Analysis of Intermethod Agreement for Global Left Ventricular Function**

Comparison of the reference standard, magnetic resonance imaging (MRI), with the results of the 4 other tests using Bland-Altman analysis. In this Bland-Altman analysis, the mean of the difference of MRI and the index tests is given by the **solid circle** with their limits of agreement (95% confidence intervals, ±1.96 SD). 64-row computed tomography (CT) did not overestimate or underestimate **(A)** ejection fraction (EF), **(C)** end-diastolic volume (EDV), or **(D)** end-systolic volume (ESV) in comparison with MRI, but significantly overestimated **(B)** stroke volume (SV). In comparison, cineventriculography (CVG) significantly overestimated all left ventricular (LV) volumes **(B to D)**, and both 2-dimensional echocardiography (2D Echo) and 3-dimensional echocardiography (3D Echo) showed a significant underestimation for **(C)** EDV and **(D)** ESV, whereas SV was underestimated significantly only by **(B)** 2D Echo. For **(A)** EF, both 3D Echo and 2D Echo showed no significant overestimation or underestimation compared with MRI. With regard to the limits of agreement, CVG and 3D Echo showed significantly larger limits of agreement ($p < 0.05$) than 64-row CT for **(A)** EF and **(B)** SV, whereas for **(C)** EDV and **(D)** ESV, there was no significant difference. Regarding 2D Echo, limits of agreement were larger for SV, but not for **(A)** EF, **(C)** EDV, and **(D)** ESV. + = significant ($p < 0.05$ overestimation vs. MRI); − = significant ($p < 0.05$ underestimation vs. MRI); # = significantly larger limits of agreement vs. 64-row CT.

significantly higher ($p < 0.001$ for all) than that of CVG, 2D Echo, or 3D Echo (Table 5). The specificity of 2D Echo ($p < 0.001$), 3D Echo ($p < 0.001$), and CVG ($p = 0.009$) was significantly better than that of 64-row CT, whereas the diagnostic accuracy of the 4 tests was not significantly different (Table 5). See Online Tables 7 through 10 for details on how all tests scored regional function on the 4-point scale.

Table 2 **Results of Global Left Ventricular Function Assessment With All 5 Diagnostic Tests in All 36 Patients**

	MRI	64-Row CT	2D Echo	3D Echo	CVG
EF (%)	55.6 ± 16.0	56.9 ± 14.7	56.3 ± 14.7	58.3 ± 17.2	59.5 ± 13.9*
EDV (ml)	131.1 ± 59.4	137.3 ± 50.0	105.3 ± 53.4*	112.8 ± 58.7*	191.0 ± 59.5*
ESV (ml)	65.6 ± 61.9	65.7 ± 51.7	51.3 ± 43.7*	52.6 ± 48.4*	81.5 ± 53.1*
SV (ml)	65.5 ± 15.6	71.7 ± 17.3*	54.0 ± 23.0*	59.4 ± 24.8	109.5 ± 28.3*
MM (g)	152.5 ± 57.8	136.2 ± 51.9*	N/A	N/A	N/A

Values are mean ± SD. *$p < 0.05$, *t* test vs. MRI, indicating significant overestimation or underestimation of this parameter by the respective test.

2D Echo = 2-dimensional echocardiography; 3D Echo = 3-dimensional echocardiography; CT = computed tomography; CVG = cineventriculography; EDV = end-diastolic volume; EF = ejection fraction; ESV = end-systolic volume; MM = myocardial mass; MRI = magnetic resonance imaging; N/A = not available; SV = stroke volume.

Table 3 Correlation Analysis Results for Global Left Ventricular Function in All 36 Patients

	64-Row CT vs. MRI	2D Echo vs. MRI	3D Echo vs. MRI	CVG vs. MRI
EF (%)	R = 0.89; p < 0.001; SEE = 6.74; S = 0.82; I = 10.3	R = 0.79; p < 0.001; SEE = 9.11; S = 0.73; I = 14.8	R = 0.79; p < 0.001; SEE = 10.69; S = 0.85; I = 9.5	R = 0.77; p < 0.001; SEE = 9.00; S = 0.67; I = 24.4
EDV (ml)	R = 0.90; p < 0.001; SEE = 22.47; S = 0.75; I = 38.6	R = 0.84; p < 0.001; SEE = 29.11; S = 0.76; I = 5.8	R = 0.82; p < 0.001; SEE = 34.24; S = 0.81; I = 6.8	R = 0.84; p < 0.001; SEE = 33.01; S = 0.84; I = 81.2
ESV (ml)	R = 0.96; p < 0.001; SEE = 14.97; S = 0.8; I = 13.1	R = 0.94; p < 0.001; SEE = 14.80; S = 0.67; I = 7.5	R = 0.92; p < 0.001; SEE = 19.45; S = 0.72; I = 5.4	R = 0.92; p < 0.001; SEE = 21.64; S = 0.79; I = 29.9
SV (ml)	R = 0.55; p = 0.001; SEE = 14.70; S = 0.61; I = 31.8	R = 0.31; p = 0.05; SEE = 22.21; S = 0.46; I = 23.9	R = 0.27; p = 0.12; SEE = 24.25; S = 0.43; I = 31.6	R = 0.44; p < 0.04; SEE = 25.74; S = 0.80; I = 57.0
MM (g)	R =0.93 p < 0.001; SEE = 19.42; S = 0.83; I = 8.9	N/A	N/A	N/A

I = intercept; R = correlation coefficient; S = slope; SEE = standard error of estimate; other abbreviations as in Table 2.

Interobserver variability for global LV function. Regarding EF, there was a significant difference between the 2 readers for MRI ($p < 0.001$), but not for 64-row CT, CVG, 2D Echo, or 3D Echo. Furthermore MRI, 2D Echo, and 3D Echo also showed significant difference ($p < 0.05$ for all) between the 2 readers for ESV and EDV (Fig. 4). In addition, for 2D Echo and 3D Echo, there was also a significant difference ($p < 0.05$ for both) for SV between the 2 readers.

The limits of agreement of CT for EF, EDV, ESV, and SV showed no significant difference from those of MRI, whereas 2D Echo showed significantly larger limits of agreement. For EF, EDV, and ESV, 3D Echo showed significantly larger limits of agreement, whereas CVG showed larger limits of agreement only for SV. Intraclass correlation regarding EF, EDV, and ESV was high for MRI, 64-row CT, 2D Echo, and 3D Echo (Online Table 11). CVG intraclass correlation was moderate only for EF.

Interobserver variability for regional LV function. There was no significant difference between the 2 readers on the per-patient level for all 5 tests, although there was a trend for significant difference with CT. CVG showed almost perfect interrater agreement (kappa = 0.94, $p = 0.99$), whereas MRI and 64-row CT both showed substantial good interrater agreement (kappa = 0.77, $p = 0.63$, and kappa = 0.69, $p = 0.06$, respectively). For 2D Echo and 3D Echo, interrater agreement was moderate (kappa = 0.46, $p = 0.29$, and kappa = 0.31, $p = 0.18$, respectively).

Discussion

This study is, to the best of our knowledge, the first head-to-head comparison of 64-row CT, CVG, 2D Echo, and 3D Echo with MRI for cardiac function assessment. 64-row CT was found to be superior in assessing global LV parameters (EF, EDV, and ESV) compared with the 3 other diagnostic tests (CVG, 2D Echo, and 3D Echo) using MRI as the reference standard. One of the reasons why 64-row CT was more accurate than the other tests may be related to the fact that for CT and MRI, similar methods for calculating global cardiac function are applied. CT and the other methods showed similar diagnostic accuracy in detecting regional wall motion deficits with MRI as the reference standard. Additionally, our results also indicate high interobserver reliability for both regional and global LV function analysis using 64-row CT. All 5 diagnostic tests were performed in 36 consecutive patients within an individual period of 24 h.

In the recent past, 64-row CT has greatly advanced as a noninvasive method for coronary angiography and also has been found to allow accurate assessment of LV function (13–15,34). For EF, the limits of agreement obtained with 64-row CT (±14.2%) in comparison with MRI were similar to those reported in previous studies using 64-row CT by Guo et al. (35) (±10.3%) and Puesken et al. (34) (±9.0%). For CVG, we also found a significant overestimation of EDV and ESV, as previously reported by other

Table 4 Comparative Per-Patient Diagnostic Performance for Regional Function

	64-Row CT	2D Echo	3D Echo	CVG
Sensitivity (%)	18/22 (82% [60–95])	11/22 (50% [28–72])*	11/22 (50% [28–72])*	16/22 (73% [50–89])
Specificity (%)	5/14 (36% [13–65])	13/14 (93% [66–100])*	14/14 (100% [77–100])*	11/14 (79% [49–95])
Positive predictive value	18/27 (67% [46–83])	11/12 (92% [62–100])	11/11 (100% [72–100])*	16/19 (84% [60–97])
Negative predictive value	5/9 (56% [21–86])	13/24 (54% [33–74])	14/25 (56% [35–76])	11/17 (65% [38–86])
Diagnostic accuracy (%)	23/36 (64% [46–79])	24/36 (67% [49–81])	25/36 (69% [52–84])	27/36 (75% [58–88])

Values are n/N (% [95% confidence interval]). *$p < 0.05$ versus 64-row CT. Further details of the cross tabulations can be found in the Online Appendix.
Abbreviations as in Table 2.

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Table 5 Comparative Per-Segment Diagnostic Performance for Regional Function

	64-Row CT	2D Echo	3D Echo	CVG
Sensitivity	126/154 (82% [75–88])	88/154 (57% [49–65])*	87/154 (56% [48–64])*	85/154 (55% [47–63])*
Specificity	392/458 (86% [82–89])	451/458 (98% [97–99])*	453/458 (99% [97–100])*	416/458 (91% [88–93])†
Positive predictive value	126/192 (66% [58–72])	88/95 (93% [85–97])*	87/92 (95% [88–98])*	85/127 (67% [58–75])
Negative predictive value	392/420 (93% [91–96])	451/517 (87% [84–90])†	453/520 (87% [84–90])†	416/485 (86% [82–89])*
Diagnostic accuracy	518/612 (85% [82–87])	539/612 (88% [85–91])	540/612 (88% [85–91])	501/612 (82% [79–85])
Youden index	0.67	0.56	0.55	0.46

Values are n/N (% [95% confidence interval]). *$p < 0.001$ versus 64-row CT. †$p < 0.05$ versus 64-row CT. Further details of the cross tabulations using the 4-point scale can be found in the Online Appendix. Abbreviations as in Table 2.

authors (14,36). This overestimation is the result of geometric assumptions (28) and the angiographic magnification error (37), which limits the comparability of CVG with the other tests for EDV and ESV. By contrast, 3D Echo significantly underestimated EDV and SV, which is in good agreement with previous investigators (38–40) who primarily attribute this underestimation to incomplete sampling of the ventricle variability (38,40) and heart rate variability (39). Interestingly, 3D Echo did not perform better than 2D Echo, which is in disagreement with the results reported by Jenkins et al. (6). One reason may be the good overall LV function of the patients included in our study, whereas 3D

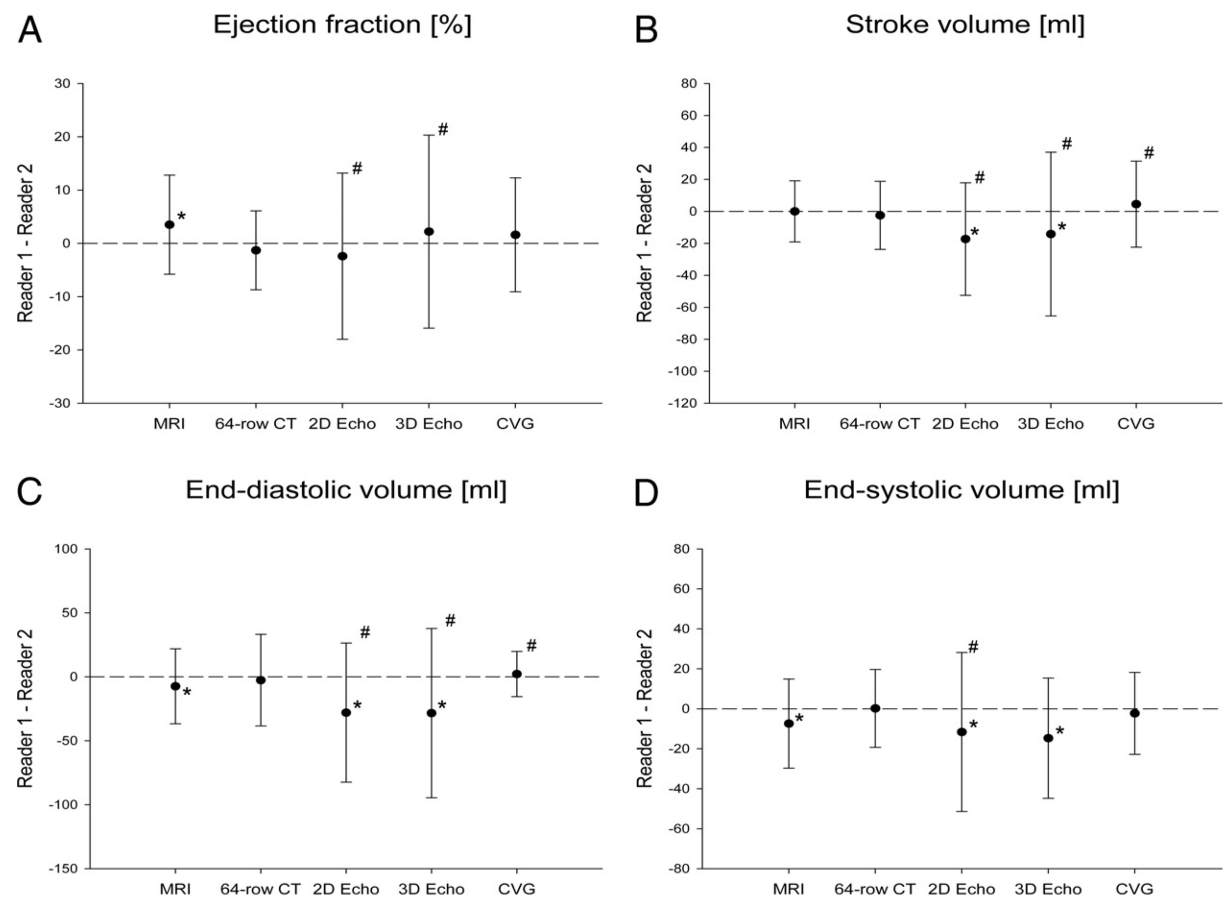

Figure 4 Summary of the Bland-Altman Analysis of Interobserver Agreement for Global Left Ventricular Function

Comparison between 2 readers for all 5 tests using Bland-Altman analysis. In this summary, the mean of the difference between 2 readers is given by the **solid circle** with their limits of agreement (95% confidence intervals, ± 1.96 SD). For 64-row CT and CVG, there was no significant difference between the 2 readers, whereas MRI showed significant difference for **(A)** EF, **(C)** EDV, and **(D)** ESV. 2D and 3D Echo showed significant differences for **(B)** SV, **(C)** EDV, and **(D)** ESV. Regarding limits of agreement, 64-row CT showed smaller limits of agreement than 2D and 3D Echo for **(A)** EF, **(B)** SV, and **(C)** EDV. When compared with CVG, 64-row CT showed significantly smaller limits of agreement for **(B)** SV, but significantly larger limits for (**C**) EDV. 64-row CT showed significantly smaller limits of agreement than 2D Echo for **(D)** ESV. *Significant ($p < 0.05$) difference by the test between the 2 readers; #Significantly larger limits of agreement between the 2 readers of the test versus MRI. Abbreviations as in Figure 3.

Echo has been shown to improve assessment of global cardiac function parameters in patients with large hearts, cardiac aneurysms, or cardiomyopathy or after myocardial infarction (8,41,42) because of the better geometrical representation. In general, the accuracy of 64-row CT for assessment of global LV function is in good agreement with the results of a recent meta-analysis including 11 studies (15 cohorts) with 252 patients examined by 4- to 16-row CT in comparison with MRI (43).

Our results are in good agreement with those of the study of Annuar et al. (44) regarding the results of CT for regional wall motion deficit detection with a sensitivity and specificity of 82% and 86%, respectively. Dewey at al. (14) also showed high sensitivity (88% and 75%, respectively) for the detection of wall motion deficits using 16-row CT. Similar to our results, Dewey et al. (14) also showed a significant superiority of CT over CVG. Although multisegment reconstruction was used to improve temporal resolution, 64-row CT is still far from the temporal resolution needed for optimal identification of the end-systolic period (acquisition window: 20 to 40 ms) (21) offered by echocardiography (33 ms) or MRI (34 ms). The poorer temporal resolution greatly limits the ability of CT to differentiate regional wall motion deficits (Online Tables 7 to 10).

Regarding interobserver agreement, our results show a high general intraclass correlation for 64-row CT, which agrees well with results previously reported (45,46). Interestingly, MRI showed significant interobserver variability despite high intraclass correlation, which may be related to the large degree of manual interaction and may be overcome with additional consented training, as reported by Beerbaum et al. (47). For 2D Echo, our results agree well with the studies of Blondheim et al. (48) and Hoffman et al. (49), which also showed good reliability (intraclass correlation coefficient = 0.78 and 0.79, respectively, vs. 0.86 for this study) for EF. In contrast, for CVG, Hoffman et al. (49) reported higher reliability regarding EF (intraclass correlation coefficient = 0.80 vs. 0.58 for this study). This again may be related to manual discrimination of cardiac boundaries as well as time points for end systole and end diastole.

Study limitations. Nevertheless, our study also has relevant limitations. One third of patients included (12 of 36) had abnormal global LV cardiac function (EF ≤55%). However, in clinical practice, cardiac CT is used rarely in those patients because its main field of application is coronary angiography in patients with low or moderate pretest probabilities of coronary artery disease (50). As a result, the number of patients with poor cardiac function is even smaller in clinical practice. Nevertheless, 64-row CT also showed accurate LV function assessment in patients with reduced cardiac function. Therefore, 64-row CT may be used in patients with contraindications to MRI (e.g., pacemakers) or patients with poor acoustic windows in echocardiography, because it provides moderate to good accuracy for global and regional LV function.

In addition, 3D Echo required acquisition of datasets during up to 6 consecutive heartbeats, which may lead to stitching artifacts because of an unstable probe position or incorrect breath hold and limits the use of 3D Echo in patients with atrial fibrillation. However, upcoming dual-beat or single-beat techniques may help to overcome this problem (51,52).

Furthermore, modern scanners use special scanning techniques such as step and shoot (53) or wide cone beam detectors (54) to allow prospective triggering, which will reduce radiation exposure to <5 mSv in almost all patients. In our study, we used retrospective triggering to allow cardiac function assessment, resulting in approximately 16 mSv. Unfortunately, prospective triggering does not allow functional assessment; however, prospective dose modulation over the RR interval allows functional assessment at the expense of only a slightly higher radiation dose (55).

Conclusions

64-row CT allows accurate and reliable evaluation of global LV function and seems to be superior to CVG, 2D Echo, and 3D Echo when MRI is used as the reference standard. Also, the diagnostic accuracy of 64-row CT in detecting wall motion deficits seems to be similar to that of CVG, 2D Echo, and 3D Echo.

Reprints requests and correspondence: Dr. Marc Dewey, Institut für Radiologie, Charité Medical School, Charitéplatz 1, 10117 Berlin, Germany. E-mail: dewey@charite.de.

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Key Words: computed tomography ▪ echocardiography ▪ left ventricular function ▪ magnetic resonance imaging.

APPENDIX

For supplemental tables and figures, please see the online version of this article.