Assessment of Cardiac Function Using Multidetector Row Computed Tomography

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Abstract: In patients with suspected or documented heart disease, a precise quantitative and qualitative assessment of cardiac function is critical for clinical diagnosis, risk stratification, management and prognosis. Cardiac CT is increasingly being used in diagnosis of coronary artery disease. Initially multi-detector row computed tomography (MDCT) was used chiefly for detecting coronary artery stenosis and assessment of cardiac morphology. Electron beam computed tomography has been shown to provide a highly accurate ejection fraction (±1%), with 50 ms image acquisition per image. Retrospective electrocardiographic gating allows for image reconstruction in any phase of the cardiac cycle. Thus, end systolic and end diastolic images can be produced to assess ventricular volumes and function. Despite lower temporal resolution than electron beam computed tomography, the ability of MDCT to assess ejection fraction is preserved. In the assessment of cardiac function, MDCT has been shown to be in good agreement with echocardiography, cineventriculography, single photon emission computed tomography and magnetic resonance imaging. The fast technical development of scanner hardware along with multisegmental image reconstruction has led to rapid improvement of spatial and temporal resolution and significantly faster cardiac scans. The same data that is acquired for MDCT angiography can also be used for evaluation of cardiac function. Considering contrast media application, radiation exposure, and limited temporal resolution, MDCT solely for analysis of cardiac function parameters seems not reasonable at the present time. However, because the data is already obtained during coronary evaluation, the combination of noninvasive coronary artery imaging and assessment of cardiac function with MDCT is a suitable approach to a conclusive cardiac workup in patients with suspected coronary artery disease. MDCT seems suitable for assessment of cardiac function by MDCT when results are held in comparison to magnetic resonance imaging as the reference standard. Given the radiation dose and contrast requirement, referring a patient to MDCT only for evaluation of function is not warranted, but rather adds important clinical information to the already acquired data during retrospective triggering for MDCT angiography.

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Received for publication January 2, 2006; accepted March 18, 2006.

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Key Words: MDCT, magnetic resonance imaging, multislice computed tomography, ejection fraction, left ventricular function

(*J Comput Assist Tomogr* 2006;30:555–563)

Ischemic heart disease is the leading cause of morbidity and mortality in industrialized countries.[1] Therefore, the diagnosis and treatment of this disease is a major issue for the health system. In patients with suspected or documented heart disease, a precise quantitative and qualitative assessment of cardiac function is critical in determining not only the severity of cardiac impairment, but also in evaluating the efficacy of treatment. The evaluation of cardiac function can provide valuable diagnostic and prognostic information.[2,3] Prognosis after myocardial infarction is closely related to the extent of myocardial necrosis and the degree of contractile dysfunction of the left ventricle (LV).[2] Ventricular volume and myocardial mass are independent predictors of morbidity and mortality in patients with coronary artery disease (CAD).[3,4] The assessment of left ventricular function is important for clinical diagnosis, management, and follow-up of these patients.[5] Additionally, serial studies performed to monitor therapeutic response require a technique that is not only accurate but also provides good interstudy reproducibility.

Measures of cardiac function should, ideally, be carried out through modalities that provide quick and noninvasive images of superior temporal and spatial resolution. Although options exist, the choice of which modality to use should be relegated to that which modality can give the most accurate and reproducible quantitative assessments of cardiac function but also offer valuable qualitative information about cardiac morphology and regional wall motion. To date, cardiac functional assessment has been performed with various noninvasive modalities, such as echocardiography,[6,7] nuclear medicine,[8] single-detector row helical computed tomography (CT),[9] Multi-detector row computed tomography (MDCT),[10,11] electron beam computed tomography (EBCT),[12,13] and magnetic resonance imaging (MRI).[14,15] In clinical practice, measurements of ventricular dimensions and function are most commonly assessed by echocardiography. In patients undergoing invasive cardiac catheterization, left ventricular volumes and cardiac function can be determined by left ventriculography based on mono- or biplane projections. In the clinical workup of patients, these methods are still the most used techniques to determine left ventricular volumes. However, both measurements rely on geometric assumptions

about ventricular structure.[16] EBCT has very high temporal and spatial resolution, allows image acquisition every 50 ms throughout the cardiac cycle, and summates data from the apex to the base of the heart, making no assumptions about geometry. The reproducibility has been demonstrated to be ±1%, making this a clinical reference standard for ejection fraction (EF).[12,13] However, this technique has significant limited availability. Cardiac MRI provides excellent temporal and spatial resolution, allows image acquisition in any desired plane, and has a high degree of accuracy and reproducibility concerning quantitative measurements. In addition MRI can be used to measure LV volume, without assumptions about LV cavity geometry. Thus, MRI is currently considered a reference standard in assessment of cardiac function.[14,15]

In the past few years, MDCT has been increasingly used for noninvasive cardiac imaging.[17,18] Initially MDCT was used chiefly for detecting coronary artery stenosis and assessment of cardiac morphology.[19,20] Because data acquisition in spiral MDCT is continuous, retrospective ECG-gating allows for image reconstruction in any phase of the cardiac cycle. Thus, end systolic and end diastolic images can be produced to assess ventricular volumes and function. In the evaluation of cardiac function, MDCT with a temporal resolution of 125–250 ms has been shown to be promising by comparing with echocardiography,[21,22] biplanar cineventriculography,[23] single photon emission computed tomography (SPECT)[24] and MRI. The fast technical development of scanner hardware in the last few years has led to a rapid improvement of spatial and temporal resolution and significantly faster cardiac scans. Consequently MDCT has become an attractive option for evaluation of coronary artery obstruction and assessment of ventricular function.

In this article, we aim to review the studies evaluating the assessment of cardiac function by MDCT in comparison to MRI as the reference standard. We also aim to discuss the role of MDCT for evaluation of cardiac function and review its current clinical applications and limitations.

STUDIES COMPARING LEFT VENTRIICULAR FUNCTIONAL ASSESSMENT BY MDCT VERSUS MRI

Mahnken et al[25] assessed the value of different image reconstruction algorithms for the assessment of LV function, using retrospectively ECG-gated MDCT of the heart in comparison to MRI as the gold standard. MDCT and cine MRI of the heart were performed in 15 patients. For MDCT, standard and multisegmental image reconstruction with improved temporal resolution were used, with a 4 × 1 mm collimation, 1.5 mm table feed per rotation (normalized pitch: 0.375) and a tube rotation time of 500 ms. Standardized multiplanar reformats in the short axis and long axis views were reconstructed from MDCT data. Left ventricular end-systolic (LVESV) and end-diastolic volume (LVEDV), stroke volume (LVSV), ejection fraction (LVEF) and myocardial mass (MM) were calculated. According to the Bland–Altman approach, the mean differences for the left ventricular volumes (LVESV, LVEDV, and LVSV) ranged from −9.6 mL to 3.1 mL with standard image and from −0.6 mL to 1.9 mL utilizing multisegmental image reconstruction with limits of agreement ranging from −26.6 mL to 12.5 mL and −15.6 mL to 15.0 mL, respectively. Applying the multisegmental image reconstruction algorithm, a significantly improved agreement with MRI data was found for LVEDV, LVSV, and EF. The mean LVEF measured by MRI was 59.8 ± 13.4%,whereas the mean EF with standard MDCT was 64.1 ± 12.9% for observer 1 and 60.6 ± 12.6 for observer 2. With multisegmental MDCT, LVEF was determined to be 60.5 ± 13.2% for observer 1 and 59.3 ± 13.1 for observer 2. For wall motion analysis, standard image reconstruction showed a significant difference to MRI with a correspondence in 84% of the 240 assessed segments, whereas multisegmental image reconstruction agreed with MRI in 92.5% of the segments. A κ-value of 0.82 for MRI and MDCT using the multisegmental image reconstruction algorithm indicated excellent agreement. The corresponding results of the Wilcoxon test showed a statistically significant difference between MRI and MDCT using standard image reconstruction algorithms ($P = 0.009$), whereas for the multisegmental image reconstruction algorithm, no significant difference was traceable ($P = 0.26$) compared with MRI. Because current MDCT scanners allow for 0.5–0.75 mm slice thickness, the accuracy of EF measurement should improve significantly.[26] For qualitative assessment of left ventricular wall motion using MRI, different slice thickness had no relevant influence.[27]

In another study, Mahnken et al[28] compared left ventricular function derived from retrospectively ECG-gated MDCT with MRI. In 16 patients (14 males, 2 females; mean age 56.8 ± 11.5 years), retrospectively ECG-gated MDCT angiography of the coronary arteries and breath-hold steady state free precession cine MRI were performed. From MDCT data sets, 20 axial image series were reconstructed every 5% of the RR interval. Multiplanar images were reformatted in the short axis orientation from axial images using standard image reconstruction algorithms. End-systolic and end-diastolic images were selected. From these images LVESV, LVEDV and LVSV, and the LVEF and MM were determined using the Simpson method and compared with MRI. Furthermore, image quality was assessed for both imaging modalities using a 4-point grading scale. All parameters were found to have an excellent correlation between MDCT and MRI data (Pearson correlation coefficient 0.95–0.99). On average, the difference between both methods was 0.5 mL for LVESV, 0.8 mL for LVEDV, 1.3 mL for LVSV, 0.9% for LVEF, and 2.3 g for MM.

Halliburton et al[29] determined if multiphasic reconstructions of the MDCT data used for the assessment of CAD could also be used for global functional evaluation of the LV. Fifteen patients with chronic ischemic heart disease were imaged for CAD using a contrast-enhanced restrospective ECG-gated spiral technique on a MDCT scanner. The same data were reconstructed at both end-diastole and end-systole to measure LVEDV, LVESV, and LVEF. The results were compared with values obtained using a cine true-fast imaging with steady-state precession technique on a MRI scanner. Interobserver variabilities in the measurement from MDCT images were also evaluated. For LVEF, there was substantial agreement between MDCT and MRI (intraclass correlation

coefficient of 0.825); the intermodality reproducibility for LVEF (5%) (95% CI of 2.3–6.7%) was within acceptable clinical range. However, mean values of LVEDV and LVESV with MDCT compared with cine MRI (LVEDV, 262 ± 85.6 mL and 297.2 ± 98.8 mL, LVESV, 196.2 ± 75.6 mL and 218.6 ± 90.99 mL, respectively) were significantly less for both volumes ($P < 0.015$). Intermodality variabilities for these measurements were high (15 and 13% for LVEDV and LVESV, respectively). Interobserver variabilities for all values were acceptable (6%, 8%, and 15% for LVEDV, LVESV, and LVEF, respectively). For the measurement of LVESV, a pattern of bias between MDCT and MRI (r = 0.62) was detected suggesting that the difference between techniques increased as LVESV increased. For LVESV values ≥300 mL, the mean absolute difference between MDCT and MRI was 56.4 mL (n = 4); for LVESV values <300 mL, the mean absolute difference was 16.6 mL (n = 11) ($P = 0.002$). However, no significant bias existed in the measurement of LVEDV with MDCT and MRI (r = 0.26, $P = 0.341$), indicating that the mean difference between the 2 modalities was consistent across the range of LVEDV values. Also, no pattern of bias was observed between MDCT and MRI for the calculation of LVEF (r = 0.30, $P = 0.272$). The intraclass correlation coefficient for LVEF was 0.825 with 95% CI of 0.619–0.925, indicating substantial agreement. Potential sources of error during the acquisition and reconstruction of MDCT images affecting image quality and the accuracy of measurement of LV volumes included the temporal resolution, enhancement of the blood pool, cardiac motion, and respiratory motion. A MDCT method with 250 ms temporal resolution was compared with a MRI method with 32 ms temporal resolution.

Grude et al[11] compared left ventricular myocardial function determined by ECG-gated MDCT with MRI in a sample of 30 patients with known or suspected CAD. LVEDV (147 ± 27 mL) and LVESV (65 ± 22 mL) determined in short axis orientation by means of MDCT correlated well to the respective MRI measurements (LVEDV, 133 ± 27 mL, r = 0.80, $P < 0.001$; LVESV, 48 ± 19 mL, r = 0.89, $P < 0.001$). LVEF (MDCT, 56 ± 9%, MRI 65 ± 8%) showed a good correlation as well (r = 0.85, $P < 0.001$). LVSV by means of MDCT (82 ± 15 mL) showed a moderate correlation (r = 0.77, $P < 0.001$) compared with the respective MRI data (85 ± 17 mL). There was a significant overestimation of the mean LVEDV and LVESV by means of MDCT. The mean differences between MDCT and MRI LV volume measurements were 14.2 ± 17.3 mL for LVEDV (95% CI 7.7–20.6 mL; $P < 0.001$; maximum difference ± 46.6 mL) and 17.8 ± 10.3 mL for LVESV (95% CI 14.0–21.6 mL; $P < 0.001$; maximum difference ± 38.0 mL). This resulted in a significant under estimation of LVEF by –8.5 ± 4.7% (95% CI –10.2 to –6.7%; $P < 0.001$; maximum difference –17.0%) by MDCT. The mean difference of –3.4 ± 11.1 mL between MDCT, LVSV, and MRI LVSV (95% CI –7.6–0.8 mL; maximum –22.6 mL) was not significant ($P = 0.11$). However, the study population consisted of patients with basically normal LVs and results of the study cannot be generalized to patients with significantly impaired global or regional ventricular function.

In a similar fashion, Koch et al[30] determined global and regional left ventricular function from retrospectively gated MDCT in 19 patients by using 2 different semi-automated analysis tools and correlated the results with those of MRI. For multiplanar CT reformations /3-dimensional images, mean LVEDV (144.4/142.8 mL ± 67.5/67.1) and LVESV (66.4/68.7 mL ± 52.1/49.9) as determined with MDCT correlated well with MRI measurements (147.6 ± 67 [r = 0.98/0.96] and 73.3 mL ± 55.5 [r = 0.98/0.98], respectively [<0.001]). LVSV (77.6/74.1 ± 19.2/23.4 mL for MDCT vs. 74.4 mL ± 18.4 for MRI, r = 0.92/0.74) and LVEF (58.6/55.9% ± 13.5/13.7 for MDCT vs. 55.6% ± 13.5 for MRI, r = 0.95/0.91) also showed good correlation ($P < 0.001$). Regional wall motion analysis revealed agreement between CT and MRI in 316/323 (97.8%) myocardial segments.

Juergens and colleagues[10] determined LV volumetric and functional parameters from retrospectively ECG-gated 4-channel MDCT by using semi-automated analysis software in 30 patients known to have or suspected of having CAD. Results were then correlated to those of MRI. Mean LVEDV (138.8 mL ± 31.9) and LVESV (53.9 mL ± 21.2) as determined with MDCT correlated well with MRI (142 mL ± 32.5 [r = 0.93] and 54.9 mL ± 22.8 [r = 0.94], respectively [$P < 0.001$]). LVEF also showed good correlation (61.6% ± 10.6 for MDCT vs. 62.3% ± 10.1 for MRI; r = 0.88) ($P < 0.001$). Bland–Altman analysis in comparison of MDCT and MRI results demonstrated a mean difference of 0.2% ± 4.9 and 0.2 mL ± 10.6 for LVEF and LVSV, respectively.

Mahnken et al[31] evaluated retrospectively ECG-gated 16-slice MDCT in comparison with MRI for assessment of global LV function and regional wall motion. Twenty one patients (18 male; mean age 65.5 ± 8.6 years) with acute myocardial infarction underwent MDCT and MRI. MDCT protocol utilized 16 × 0.75 mm^2 collimation, 3.4-mm table feed per rotation and a tube rotation time of 420 ms was used. In general, there was a good agreement between both imaging techniques for LV volumes (LVESV [r = 0.99], LVSV [r = 0.99]). Mean LVEF determined by means of MDCT was 46.9 ± 8.4, whereas MRI resulted in an LVEF of 46.9 ± 8.9% demonstrating an excellent correlation between both imaging modalities (r = 0.99). Multivariate analysis revealed significant differences for global LV function as determined by MDCT and MRI. Post hoc *t* tests showed significant differences for LVEDV, peak filling rate (PFR), and time to peak ejection rate (TPER) ($P < 0.05$). Peak ejection rate (PER), PFR, TPER, and time from end-systole to PFR (TPFR) presented a poor correlation and a wide range of scattering between MDCT and MRI. Assessing regional wall motion, there was an overall agreement in 290 of 336 myocardial segments (86.3%) with a κ-coefficient of 0.791 indicating good agreement.

Yamamuro and colleagues[24] evaluated accuracy of cardiac functional analysis with MDCT and segmental reconstruction algorithm over a range of heart rates. These results were then compared with those obtained by 2-dimensional echocardiography, ECG-gated SPECT, and MRI. In MDCT, no substantial motion artifact was observed, even in patients with a high-heart rate, when a segmental reconstruction approach was used. LVEF estimated with

MDCT agreed and correlated well with LVEF estimated with MRI (bias ± standard deviation, −1.2% ± 4.6; r = 0.96). Similarly there was good agreement and correlation for LVEDV (−0.35 ± 15.2; r = 0.97), LVESV (1.1 mL ± 8.6; r = 0.99), and LV mass (2.5 ± 15.0; r = 0.96). Bland–Altman analysis revealed no significant degree of directional measurement bias when data obtained from MDCT and segmental reconstruction algorithms were compared with data obtained from MRI. No significant difference of the mean difference from 0 was found for any parameter. Significant overestimation of LVESV ($P < 0.01$) and underestimation of LVEF ($P < 0.001$) were observed with a half-scan approach. Standard deviation of LVEF difference between MDCT and MRI was significantly less than that between echocardiography and MRI ($P < 0.001$) or that between SPECT and MRI ($P < 0.001$).

Heuscmid et al[32] measured left ventricular functional parameters using MDCT with retrospective ECG-gating and compared the results with MRI in 31 patients with suspected or known CAD. In all cases, the quality was adequate for both MDCT and MRI. MDCT and MRI had an excellent correlation for LVEDV(r = 0.86), LVESV (r = 0.91), LVEF (r = 0.87) and MM (r = 0.88), and a good correlation for LVSV (r = 0.70). The mean difference was 13.2 ± 21.9 mL for LVEDV, 8.7 ± 15.9 mL for LVESV, 4.6 ± 12.3 mL for LVSV, 1.4 ± 5.2% for LVEF, and 11.9 ± 13.8 g for MM. However, LVEDV ($P = 0.002$), LVESV ($P = 0.005$), LVSV ($P = 0.048$), and MM ($P < 0.0001$) were significantly overestimated with MDCT compared with MRI. For LVEF, no significant difference between MDCT and MRI was found ($P = 0.15$).

DISCUSSION

Left ventricular volume measurements from retrospectively ECG-gated MDCT images enables volumetric and global functional analysis that has good correlation with cardiac MRI, which is accepted as the reference method for precise quantitative LV functional analysis. Specifically LVEDV, LVESV, SV and EF measured with MDCT have shown good correlation with values obtained by MRI in various studies.[10,11,24,25,28–32]

With the use of sub-second gantry rotation times and dedicated cardiac reconstruction algorithms by means of MDCT scanners, thin-section coronary angiograms have shown ability to depict significant proximal coronary artery stenosis in patients known or suspected of having CAD.[17,33] Using spiral computed tomography technique, data acquisition covers the entire cardiac cycle. From the same thin-section MDCT data sets, diastolic and systolic image reconstructions can be generated by using a retrospective ECG-gating technique. A freely selectable distance from the preceding or following R-peak defines the data segment from the cardiac cycle that is used for image reconstruction. Finally, thin-section secondary reformations in the true short-axis orientation at diastolic and systolic windows enable calculation of LV volumes and, consequently, functional parameters.

Assessment of Left Ventricular Function

Different invasive and noninvasive imaging modalities for the quantitative and, in part, the qualitative assessment of the left ventricular performance are available, including x-ray angiography, 2-dimensional and 3-dimensional echocardiography, MRI, EBCT, and gated SPECT.[34] Two-dimensional transthorasic echocardiography is the most widely applied modality for assessment of LV function. Echocardiography is widely available and relatively inexpensive imaging modality, which can even be performed at bedside. However, it is acoustic window and operator dependent; in up to 10% of patients' definition of endocardial borders may be inadequate.[35] Moreover, 2-dimensional echocardiography is a poor modality to use in the assessment of LV volume and function when ventricular geometry is not uniform.[6,7] Mono- or biplane cine ventriculography as a part of diagnostic coronary catheter angiography is also used for the assessment of LV volumes and function. However, this method is invasive in nature and also relies on geometric assumptions to measure LV volumes, which may impair accurate estimation of LV volume and EF, especially in hearts with complex irregular shape changes. SPECT and positron emission tomography are primarily performed to assess myocardial perfusion and metabolism. In addition, ECG-gated SPECT[8,36] and gated PET with[18] F-FDG[37] offer the potential of combining 3-dimensional assessment of LV volumes and consecutively function parameters with myocardial metabolism assessment in a single examination. However, diagnostic accuracy of gated SPECT is limited both in small and large ventricles because of its restricted spatial resolution, and definition of endocardial borders in LV segments with circumscript thinning after infarction may be difficult because of very low counts from these areas.[8,36] Prospectively, ECG-gated EBCT with a temporal resolution of 50 ms has been used to evaluate cardiac function and perfusion; however, access to these systems is limited.[38,39] Although EBCT provides submillimeter in-plane spatial resolution of 0.8×0.8 mm^2, the longitudinal resolution (z axis) remains limited to 1.5-mm-slice thickness. Nonetheless, accuracy is very high, and utility is well documented and adjunct to coronary assessment with these systems.

Although MRI is currently the preferred method for cardiac volumetric analysis, the ability to obtain functional information with MDCT could have a significant clinical impact. The same data that is acquired for angiographic evaluation of the coronary arteries with MDCT can be used for functional evaluation of the affected LV, including determination of LV chamber volumes and LVEF and potentially other parameters (eg, cardiac mass and wall stress). Obtaining sufficient functional information from the MDCT angiography may obviate the added expense and possible risk to the patient from use of another imaging modality. Additional contrast injections or scans are required to derive this information.

Calculation of LV Volume

Similar to echocardiography or cardiac MRI, LV volume measurements in MDCT are based on short-axis image reformations. For global LV function assessment only, a diastolic and a systolic phase is needed: to identify the proper image reconstructions windows, a single axial image is reconstructed every 5% of the RR interval at a representative

mid-ventricular level. The appropriate reconstruction windows for the systolic and diastolic phases are visually identified as the images showing the minimum ventricular diameter (found at 25% of RR interval) and the maximum ventricular diameter (95% of RR interval).[10]

The LV volume can be measured using different approaches as follows:

1. The area–length method is primarily used in echocardiography and in cineventriculography based on a vertical or horizontal long-axis view. The ventricular area (A) and the length from apex to the mitral valve plane (L) are used to calculate the LV volume (LV_{Vol}) according to the formula
2. Simpson method, primarily used in cardiac MRI, EBCT, and MDCT, employs contiguous, short-axis images of the LV: LV_{Vol} is calculated by adding all cross-sectional areas (A) multiplied with the section thickness (S) as
3. A threshold-based "region growing algorithm" measurement is achieved using a segmentation technique in imaging modalities that depict density or signal intensity differences between myocardium and cardiac chambers. The sum of all contiguous voxels exceeding a predefined attenuation threshold represents the total chamber volume. Simpson method and direct volumetry do not rely on geometric assumptions and thus are more accurate than the area–length method for LV volumes determination, calculation of LVEF, LVSV, and cardiac output.

$$LV_{Vol} = 8/3 \times A/\pi L$$

$$LV_{Vol} = \sigma A_N \times S.$$

LVEF is determined by the formula

$$EF = (EDV - ESV)/EDV \times 100\%.$$

The performance of automatic segmentation algorithms for MDCT is very sensitive to adequate contrast opacification. The delineation of the trabeculae (and thus the volume) can be significantly influenced by the degree of contrast opacification. The use of advanced systems (ie, –40 or 64 detector systems) allow more volume coverage and thus faster scan times. This will improve timing of the contrast opacification of the ventricle, as the scans are obtained within 5–12 seconds with 64-row MDCT.[17,33]

Spatial and Temporal Resolution

For precise qualitative and quantitative assessment of the LV function, imaging with a high-temporal and spatial resolution is mandatory.[40] ECG-gated MDCT provides an excellent spatial resolution with an advantageous signal-to-noise ratio. Although its temporal resolution using standard image reconstruction algorithms is limited, a clear differentiation between systolic and diastolic images is possible even with a temporal resolution of 125–250 ms. Nevertheless, ECG-gated MDCT has a relatively low temporal resolution compared with EBCT with a temporal resolution of up to 50 ms[41] or cine MRI with 20 phases per cardiac cycle. This limitation potentially leads to motion artifacts, especially during systole and atrial contraction.[42] Because of limited temporal resolution, systolic images obtained in patients with a higher heart rate, are of lower quality[43,44] and may impair delineation of endocardial contours.

Initial studies on the determination of volumetric and functional LV parameters with MDCT showed that results for LVESV slightly overestimated those determined with biplanar cineventriculography[23,45] and cine MRI.[24,46] Consequently, LVEF and LVSV were underestimated. It is likely that the limited temporal resolution of 125–250 ms achieved with 4-channel multi-detector row technology is the reason for impaired depiction of minimal systolic LV volumes and, hence, an overestimation of LVESV. Although the duration of the total electromechanical systole is about 300 ms, the minimal ventricular volume is maintained for only 80–200 ms. Because of the possible temporal resolution of 125–250 ms provided by MDCT system with use of 4-channel detectors, the precise definition and depiction of the peak or minimal systolic LV volume might be impaired. Ritchie et al demonstrated that a temporal resolution of about 20 ms is needed to completely avoid motion artifacts in cardiac imaging by computed tomography imaging.[47] Therefore, a further increase in the temporal resolution in cardiac MDCT would be desirable. Two strategies are possible to achieve this goal: first, shortening of the gantry rotation time as introduced with the most recent generation of MDCT scanners;[17,33,48] and second, utilization of more gantry rotations and consecutively more RR-intervals for image reconstruction using multisegmental image reconstruction algorithms.[27,49] This multisegmental image reconstruction increases the effective temporal resolution through implementation of segmented reconstruction techniques that utilize data from multiple cardiac cycles to create each image.[50,51] Thus, smaller portions of the image are obtained from consecutive heart beats to create on image, allowing for less than 100 ms effective temporal resolution. Improvement in the measurement of LV volumes with MDCT has been demonstrated for images reconstructed using segmented algorithms to effectively increase temporal resolution to 90–250 ms (depending on heart rate) for a gantry rotation time equal to 500 ms.[52] The limitation of this technique (multisegmental reconstruction) is the influence of nonuniformity of ventricular contraction between beats. However, this limitation is less pronounced for volumetry than for coronary artery evaluation. Reduction of the actual time required to reconstruct each image is anticipated with impending hardware upgrades by most MDCT scanner manufacturers and may further improve determination of ventricular volume with MDCT.

A more rapid rotation time (up to 0.33 s per rotation) has been attained with MDCT,[53] which will make it possible to shorten and stabilize the temporal resolution with a segmental approach. Furthermore, the introduction of dual source CT, the temporal resolution will decrease to 83 ms in single segment reconstructions.[54]

Effect of Heart Rate

For functional analysis it is crucial that no medication influencing the patient's heart rate or myocardial contractility is applied before MDCT or MRI examination. Artificially reduced heart rate or contractility of the myocardium may

alter the functional parameters. In those patients, functional analysis will not be of value, because the measurements will not reflect the patient's cardiac performance. As the temporal resolution of cardiac 4-detector row MDCT is not yet sufficient to image the coronary arteries at higher heart rates (>70 bpm) without motion artifacts, cardiac MDCT is regularly performed after application of beta-blockers to reduce heart rate.[43] Recent reports show that the use of beta-blockers is effective in lowering heart rates and reducing motion artifacts.[19] The use of dual-source CT may potentially diminish the need for beta-blockers and improve both volume and EF measures.

Radiation

Radiation dose reduction is clinically important. A large helical pitch, reduced tube current, increased number of detector rows, and faster rotation time can be used to reduce the radiation dose. For example, a larger helical pitch will lead to reduced radiation exposure. When the helical pitch is greater, however, the temporal resolution with a segmental approach becomes worse, which may decrease data fidelity not only for MDCT coronary information but also for functional analysis. Reduced tube current would serve to directly reduce radiation exposure. Reduced tube current will, however, cause increased image noise.[55] Recently, MDCT scanners equipped with more detector rows and a faster rotation time have not resulted in reduction of the radiation dose. The dose with 64 MDCT scanners are similar to those studies performed with 16 detector systems.[17,33] However, lowering tube current during unneeded phases of the cycle[56] is effective for radiation dose reduction. This reduces the image quality (increases image noise) of those phases obtained during dose reduction (systole, early diastole), while maintaining high resolution images during mid-late diastole for coronary artery evaluation (Figs. 1A–B). Because higher resolution images are needed to evaluate the small coronary arteries and plaque composition, only high resolution images during diastole (when motion is minimized) are required. Although the image quality is generally acceptable during tube current reduced phases for wall motion and volume changes, the effect this has on the reliability of functional analysis must be established.

Because MDCT is a true volumetric modality, theoretically enlarged or grossly deformed hearts should not influence the accuracy of these measurements. Recent studies demonstrated that even in patients with LV dysfunction or LV dilatation, global cardiac function parameters were accurately determined by 16-slice CT.[57,58] Reproducibility of global function parameters also seems within the expected norm for other modalities. The interobserver variability was from 2% to 11% for LVEDV and from 6% to 9% for LVESV; corresponding values for CMR are 2–6%.[59]

MDCT Versus MRI

Currently, cardiac MRI is the noninvasive diagnostic standard of reference for determination of LV volumes and global as well as regional LV myocardial function, demonstrating a high diagnostic accuracy and low inter- and intra-observer variability.[14,60] Advantages of cardiac

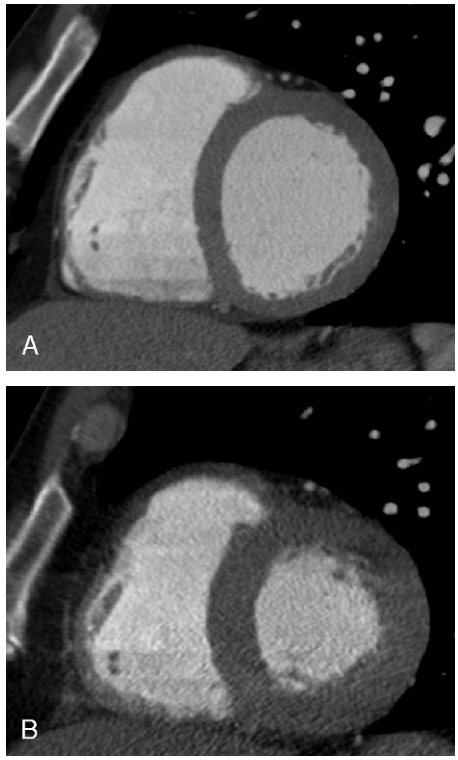

FIGURE 1. A, High resolution image obtained with high tube current during end-diastole (85% of the cardiac cycle). The contrast-to-noise ratio is high and there is little background noise, allowing for accurate depiction of the coronary arteries, plaque composition and wall motion, and mass and volumes. B, Lower resolution obtained during tube modulation, when the tube current is reduced. While there is increased noise on the image, it is still very adequate for evaluation of wall motion, LV mass and volumes of chambers (40% of the cardiac cycle). Thus, use of dose modulation should still allow accurate depiction of EF and volumes, while reducing radiation dose of the cardiac CT evaluations.

MRI compared with MDCT are the lack of radiation exposure, avoidance of iodinated contrast media, and improved temporal resolution. Furthermore, short-axis images are readily available, and time-consuming secondary reformations required in cardiac MDCT are not needed with cardiac MRI. However, in patients with dyspnea and heart failure, MDCT has the advantage of being fast with regard to breath-hold data acquisition and is suitable for patients with pacemakers and implanted defibrillators. Respiratory motion during the MDCT examinations can affect image quality and, subsequently, volume measurements. With MDCT, data are usually acquired within one prolonged breathold (8–15 s) compared with repetitive short breatholds for cine MRI. Images from both modalities are susceptible to degradation of image quality resulting from any imperfect sinus rhythm. The MDCT images should, in theory, be less susceptible to cardiac arrythmias than the MRI images acquired because of retrospective referencing of the ECG signal with MDCT versus prospective referencing with MRI. Furthermore, in comparison to EBCT, MDCT

assesses LV functional parameters in the anatomically true short-axis orientation, as it is also applied in ECG and MR imaging. In contrast, the fixed setup of an electron-beam CT scanner results in volumetric measurements based on assumption of short-axis orientation.[61]

Limitations of CT for EF Measurement

While studies suggest that the temporal resolution one may attain is less than 100 ms, with multisegment reconstruction, with a gantry rotation speed of 330 ms with the latest generation scanners, the best temporal resolution one can get is 165 ms using half-scan methods. This means that the phase that is called end-systole may be as much as 82.5 ms before or after end-systole. Therefore, end-systole is always overestimated and EF then underestimated. This systematic offset is demonstrated in every published study.[10,11,24,27,30,62–64] For example, the study by Dewey et al[64] demonstrated, "Bland–Altman analysis showed minor systematic overestimation of end-diastolic (10.7 mL) and end-systolic volumes (5.6 mL) and underestimation of EF (2.1%) with MSCT as compared with MRI." Whether dual-source CT improves these measures needs to be validated, but with improved temporal resolution, this is a possibility.

The strict relation between gantry rotation time and length of the acquisition window (temporal resolution) can be overcome with the use of multisegmental reconstruction.[61,64,65] Thus, correlations between CT and MR while uniformly excellent, demonstrate a systematic offset of the absolute values. Furthermore, most of these studies are not in patients with LV dysfunction. How well these measures will correlate over a larger spectrum of LV dysfunction remains to be seen. One study of electron beam tomography showed excellent correlation across a wide spectrum of EFs, however, these type of studies need to be reproduced with MDCT.[66] Furthermore, only 1 study of MDCT has compared results with spect nuclear imaging, cineventriculography, and echocardiography in a head-to-head design in a single study.[67] These are examples of studies needed to determine the usefulness of MDCT in comparison to commonly applied tools like cineventriculography and echocardiography (with MRI as the reference standard). Arrhythmias make interpretation more difficult with CT and the possibility of real time imaging in MRI may be a significant improvement in these cases.

Radiation doses remain high for cardiac CT evaluations, especially compared with no radiation approaches such as echocardiography and MRI. The radiation dose should substantially reduce by the introduction of an ECG triggered tube current modulation. Studies demonstrate between a 28–48% dose reduction with ECG dose modulation, depending on the baseline heart rate.[56,68] With the use of tube current modulation, however, the end-systolic reconstruction phase may lie in the phase of reduced tube current and consecutively may be hampered because of decreased image quality (Fig. 1). Of note, the quality of the reduced radiation dose image is generally adequate to make measures of LV volumes and EF. However, this approach to evaluate cardiac function when using dose modulation will be limited by noise, especially problematic in obese patients. Without dose modulation, the radiation dose of cardiac CT increases significantly.[68] Finally, the use of a beta-blocker restricts the interpretation of a study as the cardiac function may be influenced.

Still, the ability to accurately measure EF, wall motion and volumes, without additional protocols or injections, adds to the value of the cardiac CT examination.

Processing time is still somewhat long because of the large datasets needed for MDCT. In the study by Dewey et al, the post-processing time was moderately but significantly longer with the MDCT software (15.9 ± 2.8 min) than necessary for MRI (14.0 ± 2.5 min, $P < 0.01$), mainly as a result of the longer time required for uploading of the MSCT datasets, which were on average 54 times larger (1.3 GB).[64] However, newer workstations and better workstation applications will continue to shorten this analysis time.

Further Development

Progress concerning a more accurate determination of end systolic frames and may be analysis of regional myocardial function can be expected from MDCT systems with increased rotation speeds and a concomitant increase in temporal resolution. In recent MRI studies, a substantially significant decrease of LVEF was observed with increasing temporal resolution, which is more relevant than reduction of spatial resolution of less than 2 mm.[62] The new generation of MDCT systems offer simultaneous acquisition of up to 64 submillimeter sections and provide a reduced gantry rotation time of 330 ms. Dual source CT with theoretical temporal resolution of 83 ms further adds to the possibility for better imaging, although no validation of this scanner is currently available.[54]

CONCLUSIONS

Contrast media application, radiation exposure and limited temporal resolution, and cardiac MDCT solely for analysis of cardiac function parameters seems not reasonable at the present time. Because there is no additional imaging requirement (all data is available with primary acquisition) to measure cardiac function once the anatomic data is obtained, routine measure of EF seems reasonable. The combination of non invasive coronary artery imaging and assessment of cardiac function with a single breath-hold MDCT study will provide a more conclusive cardiac workup in patients with suspected CAD. The new generation of MDCT systems with improved temporal resolution may enable analysis of regional LV myocardial wall motion abnormalities.

REFERENCES

1. Murray CJ, Lopez AD. Alternative projections of mortality and disability by cause 1990–2020: Global Burden of Disease Study. *Lancet*. 1997;349(9064):1498–1504.
2. Sanz G, Castaner A, Betriu A, et al. Determinants of prognosis in survivors of myocardial infarction: a prospective clinical angiographic study. *N Engl J Med*. 1982;306(18):1065–1070.
3. White HD, Norris RM, Brown MA, et al. Left ventricular end-systolic volume as the major determinant of survival after recovery from myocardial infarction. *Circulation*. 1987;76(1):44–51.
4. Hammermeister KE, DeRouen TA, Dodge HT. Variables predictive of survival in patients with coronary disease. Selection by univariate and multivariate analyses from the clinical, electrocardiographic, exercise,

arteriographic, and quantitative angiographic evaluations. *Circulation*. 1979;59(3):421–430.
5. The-Multicenter-Postinfarction-Research-Group. Risk stratification and survival after myocardial infarction. *N Engl J Med*. 1983;309:331–336.
6. Buck T, Hunold P, Wentz KU, et al. Tomographic three-dimensional echocardiographic determination of chamber size and systolic function in patients with left ventricular aneurysm: comparison to magnetic resonance imaging, cineventriculography, and two-dimensional echocardiography. *Circulation*. 1997;96(12):4286–4297.
7. Qin JX, Johns M, Shiota T, et al. Validation of real-time three-dimensional echocardiography for quantifying left ventricular volumes in the presence of a left ventricular aneurysm: in vitro and in vivo studies. *J Am Coll Cardiol*. 2000;36(3):900–907.
8. Bavelaar-Croon CD, Kayser HW, van der Wall EE, et al. Left ventricular function: correlation of quantitative gated SPECT and MR imaging over a wide range of values. *Radiology*. 2000;217(2):572–575.
9. Mochizuki T, Murase K, Higashino H, et al. Two- and three-dimensional CT ventriculography: a new application of helical CT. *AJR Am J Roentgenol*. 2000;174(1):203–208.
10. Juergens KU, Grude M, Maintz D, et al. Multi-detector row CT of left ventricular function with dedicated analysis software versus MR imaging: initial experience. *Radiology*. 2004;230(2):403–410.
11. Grude M, Juergens KU, Wichter T, et al. Evaluation of global left ventricular myocardial function with electrocardiogram-gated multidetector computed tomography: comparison with magnetic resonance imaging. *Invest Radiol*. 2003;38(10):653–661.
12. Lipton MJ, Higgins CB, Farmer D, et al. Cardiac imaging with a high-speed Cine-CT Scanner: preliminary results. *Radiology*. 1984;152(3):579–582.
13. Lipton MJ, Farmer DW, Killebrew EJ, et al. Regional myocardial dysfunction: evaluation of patients with prior myocardial infarction with fast CT. *Radiology*. 1985;157(3):735–740.
14. Pattynama PM, Lamb HJ, van der Velde EA, et al. Left ventricular measurements with cine and spin-echo MR imaging: a study of reproducibility with variance component analysis. *Radiology*. 1993;187(1):261–268.
15. Bellenger NG, Burgess MI, Ray SG, et al. Comparison of left ventricular ejection fraction and volumes in heart failure by echocardiography, radionuclide ventriculography and cardiovascular magnetic resonance; are they interchangeable? *Eur Heart J*. 2000;21(16):1387–1396.
16. Missouris CG, Forbat SM, Singer DRJ, et al. Echocardiography overestimates left ventricular mass: a comparative study with magnetic resonance imaging in patients with hypertension. *J Hypertens*. 1996;14(8):1005–1010.
17. Raff GL, Gallagher MJ, O'Neill WW, et al. Diagnostic accuracy of noninvasive coronary angiography using 64-slice spiral computed tomography. *J Am Coll Cardiol*. 2005;46(3):552–557.
18. Achenbach S, Giesler T, Ropers D, et al. Detection of coronary artery stenoses by contrast-enhanced, retrospectively electrocardiographically-gated, multislice spiral computed tomography. *Circulation*. 2001;103(21):2535–2538.
19. Ropers D, Baum U, Pohle K, et al. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation*. 2003;107(5):664–666.
20. Hoffmann U, Moselewski F, Cury RC, et al. Predictive value of 16-slice multidetector spiral computed tomography to detect significant obstructive coronary artery disease in patients at high risk for coronary artery disease: patient-versus segment-based analysis. *Circulation*. 2004;110(17):2638–2643.
21. Dirksen MS, Jukema JW, Bax JJ, et al. Usefulness of dynamic multislice computed tomography of left ventricular function in unstable angina pectoris and comparison with echocardiography. *Am J Cardiol*. 2002;90(10):1157–1160.
22. Schuijf JD, Bax JJ, Salm LP, et al. Noninvasive coronary imaging and assessment of left ventricular function using 16-slice computed tomography. *Am J Cardiol*. 2005;95(5):571–574.
23. Juergens KU, Grude M, Fallenberg EM, et al. Using ECG-gated multidetector CT to evaluate global left ventricular myocardial function in patients with coronary artery disease. *AJR Am J Roentgenol*. 2002;179(6):1545–1550.
24. Yamamuro M, Tadamura E, Kubo S, et al. Cardiac functional analysis with multi-detector row CT and segmental reconstruction algorithm: comparison with echocardiography, SPECT, and MR imaging. *Radiology*. 2005;234(2):381–390.
25. Mahnken AH, Spuentrup E, Niethammer M, et al. Quantitative and qualitative assessment of left ventricular volume with ECG-gated multislice spiral CT: value of different image reconstruction algorithms in comparison to MRI. *Acta Radiol*. 2003;44(6):604–611.
26. Sorrentino MJ. Echocardiographic determination of myocardial mass: a review. *Am J Physiol Imaging*. 1988;3(2):109–113. Review.
27. Kachelriess M, Kalender WA. Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart. *Med Phys*. 1998;25(12):2417–2431.
28. Mahnken AH, Spüntrup E, Wildberger JE, et al. Quantification of cardiac function with multislice spiral CT using retrospective EKG-gating: comparison with MRI. *Rofo*. 2003;175(1):83–88.
29. Halliburton SS, Petersilka M, Schvartzman PR, et al. Evaluation of left ventricular dysfunction using multiphasic reconstructions of coronary multi-slice computed tomography data in patients with chronic ischemic heart disease: validation against cine magnetic resonance imaging. *Int J Cardiovasc Imaging*. 2003;19(1):73–83.
30. Koch KE, Oellig F, Kunz P, et al. Assessment of global and regional left ventricular function with a 16-slice spiral-CT using two different software tools for quantitative functional analysis and qualitative evaluation of wall motion changes in comparison with magnetic resonance imaging. *Rofo*. 2004;176(12):1786–1793.
31. Mahnken AH, Koos R, Katoh M, et al. Sixteen-slice spiral CT versus MR imaging for the assessment of left ventricular function in acute myocardial infarction. *Eur Radiol*. 2005;15(4):714–720.
32. Heuschmid M, Rothfuss J, Schröder S, et al. Left ventricular functional parameters: comparison of 16-slice spiral CT with MRI. *Rofo*. 2005;177(1):60–66.
33. Leber AW, Knez A, von Ziegler F, et al. Quantification of obstructive and nonobstructive coronary lesions by 64-slice computed tomography: a comparative study with quantitative coronary angiography and intravascular ultrasound. *J Am Coll Cardiol*. 2005;5;46(1):147–154.
34. Greenberg SB, Sandhu SK. Ventricular function. *Radiol Clin North Am*. 1999;37(2):341–359. vi (Review).
35. Malm S, Frigstad S, Sagberg , et al. Accurate and reproducible measurement of left ventricular volume and ejection fraction by contrast echocardiography: a comparison with magnetic resonance imaging. *J Am Coll Cardiol*. 2004;1;44(5):1030–1035.
36. Manrique A, Faraggi M, Vera P, et al. 201Tl and 99mTc-MIBI gated SPECT in patients with large perfusion defects and left ventricular dysfunction: comparison with equilibrium radionuclide angiography. *J Nucl Med*. 1999;40(5):805–809.
37. Slart RHJA, Bax JJ, de Jong RM, et al. Comparison of gated PET with MRI for evaluation of left ventricular function in patients with coronary artery disease. *J Nucl Med*. 2004;45(2):176–182.
38. Boyd DP, Lipton MJ. Cardiac computed-tomography. *Proc IEEE*. 1983;71:298–307.
39. Woo P, Mao S, Wong S, et al. Left ventricular size determined by electron beam computed tomography predicts significant coronary artery disease and events. *Am J Cardiol*. 1997;79(9):1236–1238.
40. Setser RM, Fischer SE, Lorenz CH. Quantification of left ventricular function with magnetic resonance images acquired in real time. *J Magn Reson Imaging*. 2000;12(3):430–438.
41. Lipton MJ. Quantitation of cardiac function by cine-CT. *Radiol Clin North Am*. 1985;23(4):613–626.
42. Hong C, Becker CR, Huber A, et al. ECG-gated reconstructed multi-detector row CT coronary angiography: effect of varying trigger delay on image quality. *Radiology*. 2001;220(3):712–717.
43. Schroeder S, Kopp AF, Kuettner A, et al. Influence of heart rate on vessel visibility in noninvasive coronary angiography using new multislice computed tomography: experience in 94 patients. *Clin Imaging*. 2002;26(2):106–111.
44. Sechtem U, Pflugfelder P, Higgins CB. Quantification of cardiac function by conventional and cine magnetic resonance imaging. *Cardiovasc Intervent Radiol*. 1987;10(6):365–373.
45. Wintersperger BJ, Hundt W, Knez A, et al. Left ventricular systolic function assessed by ECG gated multirow-detector spiral computed tomography (multi-detector row CT): comparison to ventriculography. *Eur Radiol*. 2002;12:S192.
46. Juergens KU, Fischbach R, Grude M, et al. Evaluation of left ventricular

function by retrospectively ECG-gated multislice spiral CT in comparison to cine magnetic resonance imaging. *Eur Radiol*. 2002;12:S191.
47. Ritchie CJ, Godwin JD, Crawford CR, et al. Minimum scan speeds for suppression of motion artifacts in CT. *Radiology*. 1992;185(1):37–42.
48. Heuschmid M, Kuttner A, Flohr T, et al. Visualization of coronary arteries in CT as assessed by a new 16 slice technology and reduced gantry rotation time: first experiences. *Rofo*. 2002;174(6):721–724.
49. Boese JM, Bahner ML, van Kaick G. Optimizing temporal resolution in CT with retrospective ECG gating. *Radiologe*. 2000;40(2):123–129.
50. Bruder H, Schaller S, Ohnesorge B, et al. High temporal resolution volume heart imaging with multirow computed tomography. *SPIE*. 1999;3661:420–432.
51. Kachelriess M, Ulzheimer S, Kalender WA. ECG-correlated image reconstruction from subsecond multi-slice spiral CT scans of the heart. *Med Phys*. 2000;27(8):1881–1902.
52. Halliburton SS, Boese JM, Flohr TG, et al. Improved volumetric analysis of the left ventricle using cardiac multi-slice computed tomography (MSCT) with high temporal resolution image reconstruction. *Radiology*. 2002;252(P):389.
53. Nieman K, Cademartiri F, Lemos PA, et al. Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. *Circulation*. 2002;106(16):2051–2054.
54. Achenbach S, Ropers D, Kuettner A, et al. Contrast-enhanced coronary artery visualization by dual-source computed tomography—Initial experience. *Eur J Radiol.* 2006;57:331–335.
55. Kopp AF, Schroeder S, Kuettner A, et al. Coronary arteries: retrospectively ECG-gated multi-detector row CT angiography with selective optimization of the image reconstruction window. *Radiology*. 2001;221(3):683–688.
56. Jakobs TF, Becker CR, Ohnesorge B, et al. Multislice helical CT of the heart with retrospective ECG gating: reduction of radiation exposure by ECG-controlled tube current modulation. *Eur Radiol*. 2002;12(5):1081–1086.
57. Juergens KU, Seifarth H, Maintz D, et al. Left ventricular function determination with Multidetector-row CT of the heart: are short-axis image reformations necessary? *Am J Roentgenol.* (in press).
58. Juergens KU, Ozgun M, Maintz D, et al. Analyse der globalenund regionalen linksventrikulären Funktion Mittels 16-Zeilen-Spiral-Computertomographie des Herzens im Vergleich zur MR-Tomographie. *Fortschr Röntgenstr*. 2005;177:S273–278.
59. Barkhausen J, Ruehm SG, Gyen M, et al. MR evaluation of ventricular function: true fast imaging with steady-state precession versus fast low-angle shot cine MR imaging: feasibility study. *Radiology*. 2001;219(1):264–269.
60. Lorenz CH, Walker ES, Morgan VL, et al. Normal human right and left ventricular mass, systolic function, and gender differences by cine magnetic resonance imaging. *J Cardiovasc Magn Reson*. 1999;1(1):7–21.
61. Kivelitz DE, Enzweiler CNH, Wiese TH, et al. Determination of left ventricular function parameters and myocardial mass: comparison of MRI and EBT. *Rofo*. 2000;172(3):244–250.
62. Miller S, Simonetti OP, Carr J, et al. MR Imaging of the heart with cine true fast imaging with steady-state precession: influence of spatial and temporal resolutions on left ventricular functional parameters. *Radiology*. 2002;223(1):263–269.
63. Juergens KU, Maintz D, Grude M, et al. Multi-detector row computed tomography of the heart: does a multi-segment reconstruction algorithm improve left ventricular volume measurements? *Eur Radiol*. 2005; 15(1):111–117.
64. Dewey M, Muller M, Teige F, et al. Evaluation of a semiautomatic software tool for left ventricular function analysis with 16-slice computed tomography. *Eur Radiol*. 2006;16:25–31.
65. Kim TH, Hur J, Kim SJ, et al. Two-phase reconstruction for the assessment of left ventricular volume and function using retrospective ECG-gated MDCT: comparison with echocardiography. *Am J Roentgenol*. 2005;185(2):319–325.
66. Baik HK, Budoff MJ, Lane KL, et al. Accurate measures of ejection fraction using electron beam tomography, radionuclide angiography, and catheterization angiography. *Int J Cardiac Imag*. 2000;16:391–398.
67. Yamamuro M, Tadamura E, Kubo S, et al. Cardiac functional analysis with multi-detector row CT and segmental reconstruction algorithm: comparison with echocardiography, SPECT, and MR imaging. *Radiology*. 2005;234(2):381–390.
68. Gerber TC, Stratmann BP, Kuzo RS, et al. Effect of acquisition technique on radiation dose and image quality in multidetector row computed tomography coronary angiography with submillimeter collimation. *Invest Radiol*. 2005;40(8):556–563.