Cardiovascular computed tomography for diagnosis and risk stratification of coronary artery disease

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Chapter 18

Diastolic heart function assessed with MDCT: feasibility study in comparison with tissue doppler

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Abstract

Diastolic left ventricular (LV) function plays an important role in patients with cardiovascular disease. Currently, 2D echocardiography using TDI has been used most commonly to evaluate diastolic LV function. Although the role of MDCT imaging for evaluation of coronary atherosclerosis has been explored extensively, its feasibility to evaluate diastolic function has not been studied.The purpose of this study was to demonstrate the feasibility of multidetector row computed tomography (MDCT) for assessment of diastolic function in comparison with 2-dimensional (2D) echocardiography using tissue Doppler imaging (TDI). Seventy patients who had undergone 64-MDCT and 2D echocardiography with TDI were enrolled. Diastolic function was evaluated using early (E) and late (A) transmitral peak velocity (cm/s) and peak mitral septal tissue velocity (Ea) (cm/s). Peak transmitral velocity (cm/s) was calculated by dividing peak diastolic transmitral flow (mL/s) by the corresponding mitral valve area (cm2). Mitral septal tissue velocity was calculated from changes in LV length per cardiac phase. Subsequently, the estimation of LV filling pressures (E/Ea) was determined. Good correlations were observed between MDCT and 2D echocardiography for assessment of E ($r=0.73$, $p<0.01$), E/A ($r=0.87$, $p<0.01$), Ea ($r=0.82$, $p<0.01$) and E/Ea ($r=0.88$, $p<0.01$). Moreover, a good diagnostic accuracy was found for detection of diastolic dysfunction using MDCT (79%). In conclusion, MDCT imaging is a feasible technique to evaluate diastolic LV function. MDCT imaging showed good correlation for the estimation of LV filling pressures when compared to 2D echocardiography. Additionally, a good agreement was found for detection of diastolic dysfunction using MDCT.

Introduction

Diastolic left ventricular (LV) function plays an important role in the evaluation of clinical symptoms, therapeutic options and prognosis in patients with cardiovascular disease.[1-4] More specifically, it has been shown that diastolic dysfunction represents an important pathological condition in patients with coronary artery disease (CAD).[5, 6]

Currently, the concept of diastology has been explored with different imaging techniques, wherein Doppler echocardiography represents the most commonly used approach for evaluation of diastolic function.[7-12] For the evaluation of diastolic function, transmitral velocity has been used frequently as a non-invasive alternative to directly measured LV filling pressures.[7, 9] However, it is important to note that several confounding factors may influence transmitral velocity and consequently transmitral velocity alone may not be the best marker for diastolic LV dysfunction.[8, 9, 13] Combined assessment of early peak transmitral velocity and early peak mitral septal tissue velocity may be more accurate for the evaluation of diastolic LV function, predominantly in patients with depressed or increased LV filling pressures.[8, 12, 13] Multidetector row computed tomography (MDCT) has emerged as a potent non-invasive imaging modality for evaluation of coronary atherosclerosis.[14, 15] Despite the introduction of prospective triggering techniques to lower the radiation dose, retrospective electrocardiographic gating remains at present the most frequently applied approach to perform cardiac MDCT in clinical practice.[16] Furthermore, it is important to note that prospective triggering can only performed in selected patients with stable and low heart rates. Accordingly, in a large number of patients MDCT images may still be acquired using retrospective ECG gating to ensure diagnostic image quality of the coronary arteries. Importantly, in these patients, functional analysis can be performed retrospectively without additional image acquisitions.

Thus far, studies have been restricted to LV systolic function analysis, [17] and no information is available on the feasibility of MDCT imaging to assess diastolic LV function. Accordingly, the present study aimed to evaluate the feasibility of MDCT for assessment of diastolic function in a direct comparison with 2D echocardiography using TDI.

Methods

Patient population, study design

Seventy consecutive patients who had been referred for 64-MDCT imaging were retrospectively selected from our clinical registry. MDCT imaging was performed to evaluate known or established CAD, and 2D echocardiography with TDI was performed to evaluate therapeutic options. Both examinations had been performed sequentially, in random order. Known CAD

was defined as previous myocardial infarction, revascularization or evidence of CAD on previous diagnostic tests. Patients without evidence of CAD on previous diagnostic tests were suspected to have CAD (and therefore referred for CT angiography). Study exclusion was based on: (1) poor MDCT image quality (2) absence of Doppler echocardiography examination within 3 months (3) valvulopathy (mitral or aortic valve dysfunction), and (4) (supra) ventricular arrhythmias. Additionally, patients with unstable angina pectoris or acute coronary syndrome were excluded from further analysis. Our Institutional Review Board does not require its approval for retrospective technical analysis of clinically obtained data, as was the case in this study.

MDCT - Data Acquisition and Analysis

MDCT imaging was performed with a 64-slice MDCT scanner (Aquilion 64, Toshiba Medical Systems, Otawara, Japan). Prior to MDCT imaging, patients were monitored for blood pressure and heart rate. Patients with a heart rate ≥65 beats/min were given metoprolol 50 or 100 mg orally, unless contra-indicated.

For the contrast-enhanced helical scan, collimation was 64x0.5 mm with a rotation time of 400 ms. Tube current and voltage were 350 mA and 120 kV. At an injection rate of 5 mL/min, 95 to 130 mL of nonionic contrast medium (Iomeron 400; Bracco, Milan, Italy) was infused in the antecubital vein. After start of contrast infusion, recurrent low-dose examinations were performed to monitor contrast arrival within the region of interest, placed in the descending aorta. The electrocardiogram (ECG) gated helical scan was automatically triggered once the predetermined threshold level of baseline +100 Hounsfield units was reached. After a preset delay of 2 seconds, scanning was performed during an inspiratory breath hold of 8 to 12 seconds.

Data were reconstructed with a slice thickness of 1 mm and a reconstruction interval of 1 mm. With the use of half reconstruction algorithms, the actual temporal resolution was 200 milliseconds. Segmented reconstruction algorithms yielded a temporal resolution of up to 50 milliseconds, depending on the actual imaging acquisition conditions (pitch, rotation time and heart rate). ECG-gated post processing software was used for to reconstruct data in short-axis orientation. Images were reconstructed at 20 intervals (0% to 95% of the R-R interval) and transferred to a separate workstation with dedicated cardiac function analysis software (Mass V2008-EXP, LKEB, Leiden, The Netherlands).[18] Contrast-enhanced scans were analyzed by an independent observer who was blinded to all other data. Significant coronary artery stenosis was defined as ≥50% luminal narrowing, whereas non-significant stenosis was defined as <50% luminal narrowing.

MDCT - Transmitral velocity

Peak transmitral velocity (cm/s) was measured in early (E) and late (A) diastole. The peak value represents the highest mean value of the measurements obtained during early and late diastole. Late peak transmitral velocity (cm/s) was measured at atrial contraction. Transmitral velocity (cm/s) measurements were based on several processing steps (Figure 1). At first, LV volumes were calculated for 20 cardiac phases (each phase represented 5% of the cardiac cycle). For each phase, automatic contour detection was performed on 1 mm sliced reconstructed short-axis images ranging from mitral valve annulus to the cardiac apex (Figure 1A, left panel). Manual corrections could be made to improve contour detection. Papillary muscles were regarded as part of the LV cavity and were included in the LV volume analyses.[19] Automatic contour detection was performed using dedicated in-house developed MASS research software package (Mass V2008-EXP, LKEB, Leiden, The Netherlands).[18] Next, LV volumes were plotted in a volume versus time curve (Figure 1A, right upper curve). In addition, changes in LV volumes between two consecutive phases (first derivative) were derived and used to calculate the transmitral flow (mL/s) per phase (Figure 1A, right lower curve). Subsequently, the maximal transmitral flow (mL/s) in early and late diastole was derived using the transmitral flow versus time curve. To allow direct comparison with 2D echocardiography, the maximal transmitral flow (mL/s) in early and late diastole was divided by their corresponding mitral valve area (cm2) (which was measured during early and late diastole, as described below), yielding an early and late peak transmitral velocity (cm/s) and the E/A.

MDCT - Mitral septal tissue velocity

Myocardial tissue velocity (cm/s) was measured at the septal level of the mitral valve annulus attachment. Measurements of peak mitral septal tissue velocity (cm/s) during early diastole (Ea) are illustrated (Figure 1B). For 20 phases, LV length (mm) was calculated as the distance between two anatomical markers, positioned at the mitral septal annulus (MA) and cardiac apex (AP) (Figure 1B, left panel). Anatomical markers were positioned at reconstructed 4-chamber views. Reconstruction of a 4-chamber view was based on several reconstruction steps. At first, a 2-chamber view was reconstructed from axial slices, directing the image slice (cardiac axis) through the cardiac apex. Consecutively, a 4-chamber view was reconstructed by positioning the image slice at two-third of the mitral valve annulus (perpendicular to the interventricular septum) using the 2-chamber view.

The LV length (mm) per phase was plotted in a LV length versus time curve (Figure 1B, right upper panel). Changes in LV length between two consecutive phases were calculated and used to generate a velocity versus time curve (Figure 1B, right lower panel). In this curve, mitral septal tissue velocities were plotted against time. For each phase, mitral septal tissue velocity (cm/s) was computed using changes in LV length and heart rate. The maximal tis-

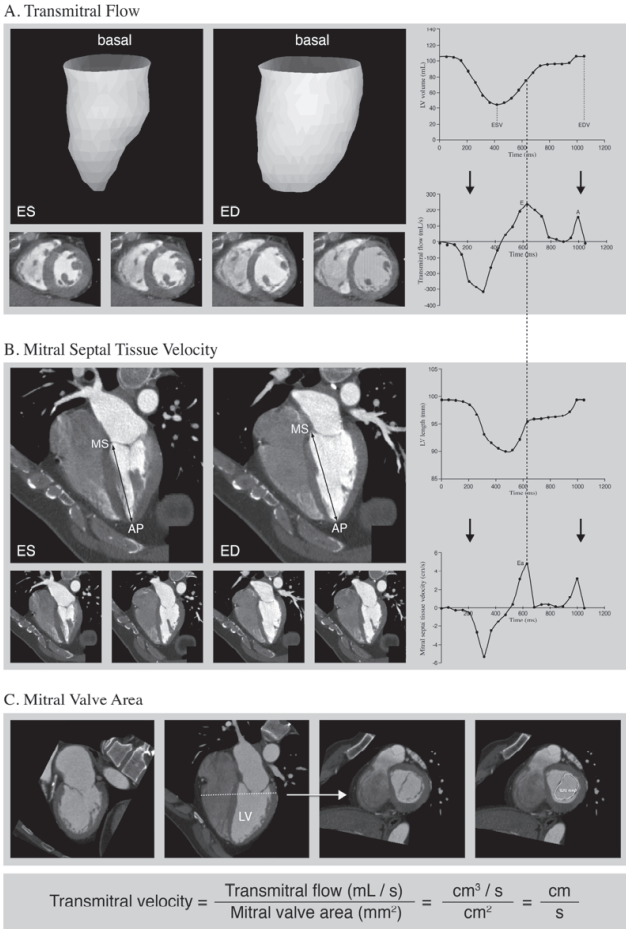

Figure 1. Diastolic left ventricular (LV) function assessed with multidetector row computed tomography (MDCT).

A Transmitral flow. LV volumes (mL) were measured for 20 phases per cardiac cycle. LV volumes (mL) were measured using short-axis images by outlining endocardial contours in each phase. LV volumes (mL) were plotted in a volume versus time curve (right upper panel). These curves were used to define the diastole, ranging from end-systolic (ES) to end-diastolic (ED) phase. Consecutively, changes in LV volumes between two consecutive phases were plotted against time (transmitral flow versus time curve) (right lower curve). Subsequently, early and late peak transmitral flow (mL/s) were derived.

B Mitral septal tissue velocity. Anatomical markers were positioned at the mitral septal annulus (MA) and the cardiac apex (AP). LV length (mm) (the distance between anatomical markers) was calculated for each phase (left panel). The LV length (mm) was plotted in a LV length versus time curve (right upper curve). Next, changes in LV length between two consecutive phases were calculated. Based on these numbers, mitral septal tissue velocities (cm/s) were calculated for each phase (velocity versus time curve, right lower panel). The early peak mitral septal tissue velocity (cm/s) (Ea) represented the maximal tissue velocity during early diastole.

C Mitral valve area. Measurements were performed at the most distal level of the mitral valve leaflets (smallest mitral valve area) using reconstructed images at peak early and late transmitral velocity. LV axis was positioned perpendicular to mid-mitral valve annulus on sagital and coronal views (left panel), yielding a 2-chamber view (panel 1). Consecutively, the 4-chamber view was reconstructed (panel 2) and mitral valve area was measured at the tip of the leaflets (panels 3 and 4) on short-axis views. To allow direct comparison, transmitral velocity (cm/s) was calculated using the following formula: peak diastolic transmitral flow (mL/s) divided by the corresponding mitral valve area (cm^2).

sue velocity (cm/s) during early diastole represented early peak mitral septal tissue velocity (cm/s) (Ea). Measurements were performed using the MASS research software package.[18]

Finally, the estimation of LV filling pressures (E/Ea) was calculated by dividing early transmitral velocity (E) (cm/s) by the mitral septal tissue velocity (Ea) (cm/s).

Reproducibility of the mitral septal tissue velocity measurements was evaluated in a subset of 15 patients who were randomly selected from the patient population. Mitral septal tissue velocity was measured twice in the subset of 15 patients according to the standardized protocol, as described above.

MDCT - Mitral valve area

Mitral valve area (cm2) was measured to enable direct comparison of volumetric indices derived from MDCT with velocity-based parameters as assessed with 2D echocardiography. In Figure 1C, the processing steps involved in mitral valve area (cm2) measurements are illustrated. Images were reconstructed with a slice thickness of 0.5 mm and a reconstruction interval of 0.3 mm.

Mitral valve area (cm2) measurements were based on different steps: the LV axis was positioned perpendicular to mid-mitral valve annulus on sagital and coronal views, yielding a 2-chamber view (panel 1). Subsequently, a 4-chamber view (panel 2) was reconstructed and manual contour detection was performed at the most distal level of the mitral valve leaflets in short-axis views (panel 3 and 4). Measurements were performed during early and late peak transmitral flow (mL/s) using a dedicated workstation (Vitrea 2; Vital Images, Minnetonka, Minnesota, USA).

The mitral valve area (cm2) was calculated to enable direct comparison with 2D echocardiography. Transmitral velocity (cm/s) was calculated by the following formula: transmitral velocity = transmitral flow (mL/s) / corresponding mitral valve area (cm2) (Figure 1). Reproducibility of the mitral valve area measurements was evaluated in a subset of 20 patients who were randomly selected from the patient population. In these patients, the mitral valve area was measured twice using the same processing steps, as described above.

Transthoracic 2D echocardiography using tissue Doppler imaging

Acquisition

Transthoracic 2D echocardiography was performed in left lateral decubitus position using a commercially available system (Vingmed Vivid-7, General Electric, Horten, Norway). Standard parasternal (long- and short-axis) and apical views (2- and 4-chamber) were obtained. In addition, continuous-wave and pulsed-wave Doppler examinations were performed. From the

4-chamber view, TDI was obtained with color Doppler frame rates exceeding 115 frames/second, depending on the sector width of the range of interest. Aliasing velocities varied between 16 and 32 cm/s and resulted from pulse repetition frequencies ranging from 500 Hz and 1 kHz. Echocardiographic analyses were performed by an independent and blinded observer.

2D echocardiography - Transmitral velocity

Transmitral velocity (cm/s) was recorded at the end of respiratory expiration (Figure 2, upper panel). Transmitral velocity (cm/s) measurements were performed using dedicated offline software (EchoPAC 7.0.0.; General Electric, Horten, Norway. Standard pulsed-wave Doppler imaging was performed to assess early (E) and late (A) peak transmitral peak velocity (cm/s). Early and late peak transmitral velocity (cm/s) were used to calculate the E/A. Doppler sample volume was placed at the tip of the mitral valve leaflets, on a 4-chamber view (20). Subsequently, early and late peak transmitral velocities (cm/s) were obtained in diastole.

2D echocardiography - Mitral septal tissue velocity

Early peak mitral septal tissue velocity (cm/s) (Ea) was assessed using color-coded TDI on a 4-chamber view. Images were obtained in end-expiration in a patient in left lateral decubitus position. Doppler velocities (cm/s) were measured from the apical 4-chamber view using a 6x6 mm sample volume positioned at the basal septal mitral valve annulus, as illustrated in Figure 2 (lower panel) (20). Color-coded images from three consecutive heartbeats were analyzed using dedicated offline software (EchoPAC 7.0.0.; General Electric, Horten, Norway). Reliable tissue Doppler curves were obtained in 67 patients.

Detection of diastolic dysfunction

To evaluate the accuracy of MDCT to detect diastolic dysfunction, diastolic function was graded in four categories using the following criteria; normal diastolic function ($\geq$1 E/A <2 and E/Ea $\leq$8), impaired relaxation pattern (diastolic dysfunction grade I) (E/A <1 and E/Ea $\leq$8), pseudonormal pattern (diastolic dysfunction grade II) ($\geq$1 E/A <2 and $\geq$9 E/Ea $\leq$12) and restrictive filling pattern (diastolic dysfunction grade III) (E/A $\geq$2 and E/Ea $\geq$13).[21] Based on these criteria, the patient population was divided into two groups; patients with normal diastolic function and patients with diastolic dysfunction (including impaired LV relaxation, pseudonormal and restrictive LV filling pattern).

Statistical analysis

Continuous data are presented as mean ± standard deviation, and categorical data are presented as absolute numbers or percentages. Comparison of MDCT and 2D echocardiography with TDI was performed using Pearson's linear regression analysis. The 95% limits of agreement were calculated using Bland-Altman analysis that plotted the mean value of differences of each pair against the average value of similar pair of data. MDCT was subtracted from 2D echocardiography

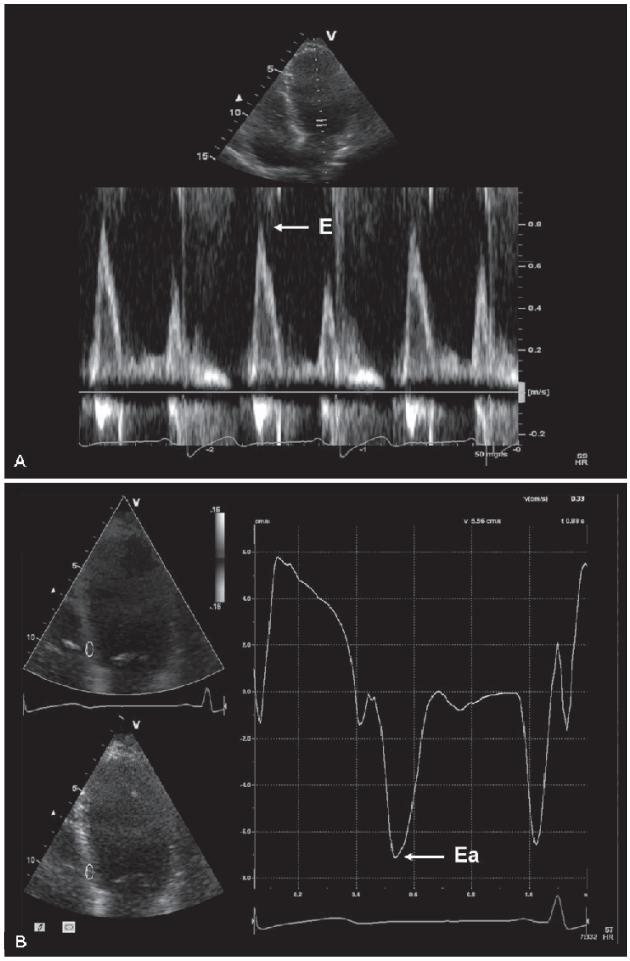

Figure 2. Evaluation of diastolic function with 2-dimensional (2D) echocardiography using tissue Doppler imaging (TDI). 2D echocardiographic assessment of pulsed-wave Doppler of early (E) transmitral velocity (cm/s) (panel A) and early diastolic peak mitral septal tissue velocity (cm/s) (Ea) at basal septal segment by TDI (panel B). The E (white arrow, panel A) and Ea (white arrow, panel B) were 0.80 m/s and -7.1 cm/s. Accordingly, the E/Ea was 11.27.

with TDI as the latter was considered the clinical standard. Reproducibility was evaluated by calculating the intraclass correlation coefficients (ICC) and an excellent agreement was defined as an ICC >0.8. Diagnostic accuracy of MDCT for detection of diastolic dysfunction was assessed using a binary approach; normal diastolic function and diastolic dysfunction (including impaired LV relaxation, pseudonormal and restrictive LV filling pattern). Corresponding sensitivity and specificity values were calculated. For these values, the 95% confidence intervals (CI) were calculated using the following formula: $p \pm 1.96$ x standard error (SE) and the SE was estimated by $\sqrt{[p(1-p)/n]}$. Statistical analyses were performed with SPSS release 16.0 (SPSS Inc, Chicago, Illinois, USA). All tests $p<0.05$ were considered statistically significant.

Results

Patient population

A total of 70 patients (46 (66%) men, mean age 55±11 years) were included. Baseline characteristics of the patient population are listed in Table 1. MDCT and 2D echocardiography were performed within 3 months and no acute coronary events or worsening of angina occurred between the examinations. No changes in the use of medication occurred between both examinations. Clinical referral for MDCT was based on suspected CAD in 58 patients and known CAD in 12 patients. Patients with known CAD included patients with previous myocardial infarction (n=10), percutaneous coronary intervention (n=7) and patients with indications of CAD on earlier diagnostic tests (n=3). Significant coronary artery stenosis (≥50% luminal narrowing) was reported in 21 (30%) patients. In total, 31 (44%) patients received beta-blocking therapy prior to MDCT imaging.

Transmitral velocity

Transmitral flow versus time curves were obtained in all patients. Mean LV end-systolic and LV end-diastolic volumes were 70±50 mL and 149±52 mL on MDCT. Accordingly, the mean LV ejection fraction was 56±13% (Table 1). Mean values for transmitral velocity are shown in Table 2. Pearson's correlation showed a good correlation for E ($r=0.73$, $p<0.01$) and E/A ($r=0.87$, $p<0.01$) (Figures 3A and 4A). Bland-Altman analysis for E showed a mean difference of 2.4±12.0 cm/s, with 95% limits of agreement ranging from -21.2 to 26.0 cm/s, whereas for E/A the mean value of difference was -0.1±0.2 with 95% limits of agreement ranging from -0.5 to 0.4 (Figures 3B and 4B). An excellent reproducibility was observed for assessment of mitral valve area (ICC 0.85, 95% CI 0.67 - 0.94).

Mitral septal tissue velocity

Velocity versus time curves were obtained for all patients. Mean values for Ea and E/Ea are shown in Table 2. A good correlation ($r=0.82$, $p<0.01$) (Figure 5A) for Ea was found. Bland-Altman analysis showed a mean value of difference of -0.5±1.6 cm/s with 95% limits of agreement ranging from -3.6 to 2.5 cm/s (Figure 5B). In addition, good correlation ($r=0.88$, $p<0.01$, Figure 6A) was reported for E/Ea with a mean value of difference of 1.0±2.9 and 95% limits of agreement ranging from -4.6 to 6.7 (Figure 6B).

An excellent reproducibility was observed for assessment of mitral septal tissue velocity (ICC 0.94, 95% CI 0.80 - 0.99).

Detection of diastolic dysfunction

Finally, diagnostic accuracy of MDCT to detect diastolic dysfunction in comparison to Doppler echocardiography was calculated (21). In total, 19 (27%) patients showed normal diastolic function, whereas 51 (73%) patients showed diastolic dysfunction using Doppler

Table 1. Baseline characteristics of study population

Men	46 (66)
Age (yrs)	55 ± 11
Suspected CAD	58 (83)
Known CAD	12 (17)
Significant coronary stenosis	21 (30)
Cardiovascular risk factors	
Diabetes mellitus	35 (50)
Systemic hypertension	43 (61)
Hypercholesterolemia	40 (57)
Current smoking	11 (16)
Positive family history	27 (39)
Medication use	
β-blockers	24 (34)
ACE-I / AT II antagonists	35 (50)
Statins	29 (41)
Diuretics	15 (21)
Anticoagulants	30 (43)
MDCT	
Heart rate (bpm)	58 ± 10
LV end-systolic volume (mL)	70 ± 50
LV end-diastolic volume (mL)	149 ± 52
LV ejection fraction (%)	56 ± 13

Table 2. Diastolic function parameters for MDCT and 2D echocardiography

	MDCT	2D echocardiography	P-value
Transmitral velocity			
E (cm/s)	59.0 ± 16.6	61.8 ± 14.5	<0.05
A (cm/s)	56.2 ± 17.4	64.8 ± 18.2	<0.05
E/A	1.1 ± 0.4	1.1 ± 0.5	<0.05
Mitral septal tissue velocity			
Ea (cm/s)	6.6 ± 2.7	6.2 ± 2.3	<0.05
E/Ea	10.5 ± 5.5	11.6 ± 6.0	<0.05

echocardiography. Of the patients with diastolic dysfunction on Doppler echocardiography, 40 patients were scored similarly using MDCT, yielding a sensitivity of 78% (95% CI 67-89%). Normal diastolic function was found in 15 of the 19 patients using MDCT, yielding a specificity of 79% (95% CI 61-97%). Overall, diagnostic accuracy for assessment of diastolic dysfunction was 79% (95% CI 69-89%).

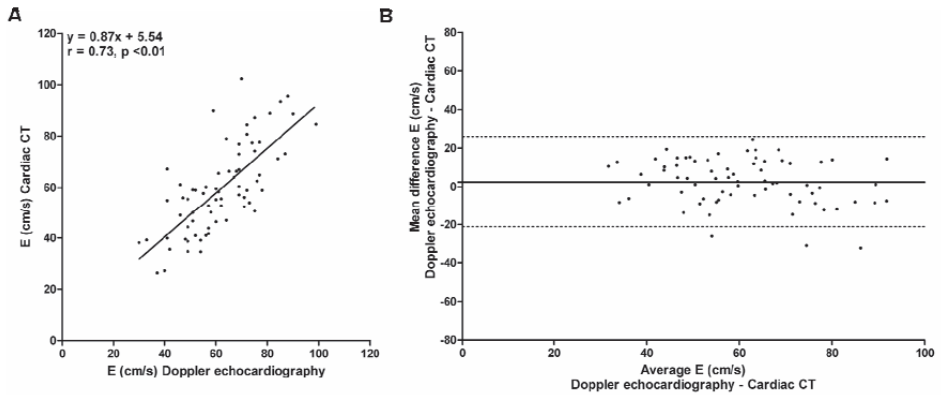

Figure 3. Comparison between 2-dimensional (2D) echocardiography and multidetector row computed tomography (MDCT) for assessment of early maximal diastolic transmitral velocity (E). A. Good correlation was observed between both techniques. B. Bland-Altman analysis showing the difference of each pair plotted against the average value of same pair of values.

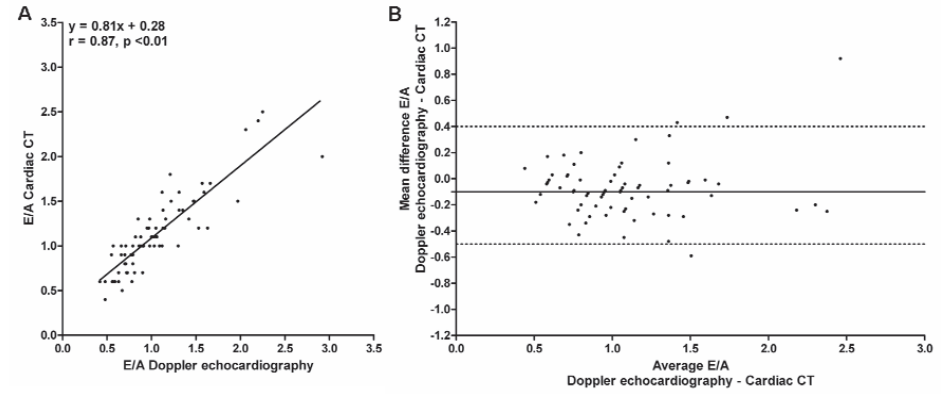

Figure 4. Comparison between 2-dimensional (2D) echocardiography and multidetector row computed tomography (MDCT) for E/A. A. Good correlation was observed between both techniques. B. Bland-Altman analysis showing the difference of each pair plotted against the average value of same pair of values.

Discussion

This study demonstrated good correlations for transmitral velocity (E and E/A) and mitral septal tissue velocity (Ea). Additionally, combined assessment of transmitral and mitral septal tissue velocity (E/Ea) representing an estimation of LV filling pressures showed good correlation between MDCT and 2D echocardiography with TDI. Finally, a good agreement was found for the detection of diastolic dysfunction using MDCT. Accordingly, the current study showed that MDCT is a feasible method for assessment of diastolic function.

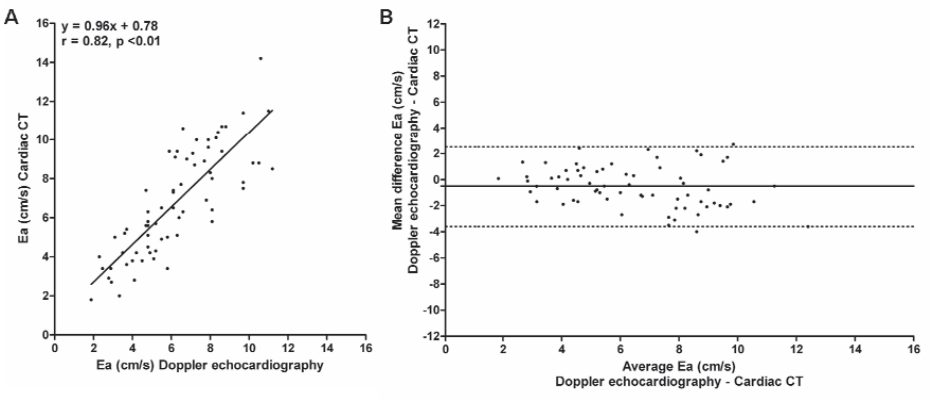

Figure 5. Comparison between 2-dimensional (2D) echocardiography and multidetector row computed tomography (MDCT) for assessment of early peak mitral septal tissue velocity (Ea). A. Good correlation was observed between both imaging techniques. B. Bland-Altman analysis showing the difference of each pair plotted against the average value of same pair of values.

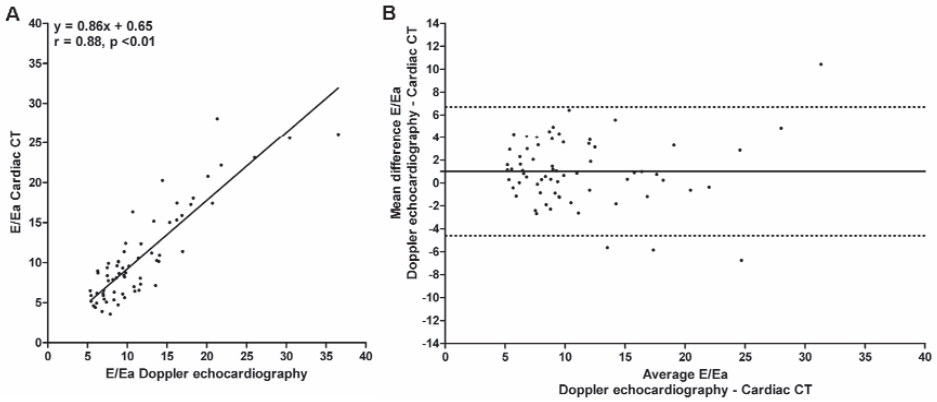

Figure 6. Comparison between 2-dimensional (2D) echocardiography and multidetector row computed tomography (MDCT) for E/Ea. A. Good correlation for E/Ea was observed between both techniques. B. Bland-Altman analysis showing the difference of each pair plotted against the average value of same pair of values.

The importance of diastolic function in patients with coronary atherosclerosis has been demonstrated in several studies.[5, 6] A recent meta-analysis pooled 3396 patients with documented myocardial infarction from 12 prospective studies and demonstrated that patients with a restrictive LV filling pattern had a significantly higher mortality rate than patients with a non-restrictive LV filling pattern (11.3 % vs. 28.7%, p<0.01).[5, 6]

Although invasive measurements of LV filling pressure are considered the most accurate approach for evaluation of diastolic LV function, they are not ideal for widespread application and follow-up examinations. Consequently, several cardiac imaging techniques (particularly Doppler echocardiography) have been used to assess transmitral velocity as a

noninvasive alternative.[7, 9] Even though complex interacting pathophysiologic mechanisms may underlie diastolic dysfunction, evaluation of diastolic LV function is most frequently based on transmitral velocity measurements alone.[7, 9, 13]

Transmitral velocity

Doppler echocardiography has been validated for the assessment of transmitral velocity as a noninvasive alternative of direct LV filling pressures.[7] Additionally, Doppler echocardiography has been compared to magnetic resonance imaging (MRI) for assessment of transmitral velocity.[11, 12] Hartiala and colleagues evaluated whether velocity-encoded cine MRI was feasible for evaluation of transmitral velocity in 10 normal volunteers.[11] Good correlations were found between Doppler echocardiography and MRI for early and late transmitral velocity and E/A ratio. In the present study, the feasibility of MDCT was demonstrated indicating good correlations between MDCT and Doppler echocardiography for early transmitral velocity ($r=0.73$, $p<0.01$) and E/A ratio ($r=0.87$, $p<0.01$). In line with the study by Hartiala et al., [11] a systematic underestimation of transmitral velocity was observed when compared to Doppler echocardiography (Table 2). These findings may be related to technical differences between MDCT and Doppler echocardiography; in particular differences in temporal resolution may play a role in the systematic underestimation of transmitral velocity with MDCT. In both studies, correlations were not excellent for transmitral velocity and this may be related to other parameters that could influence transmitral velocity measurements, including filling pressures, degree of LV relaxation, myocardial elastic recoil and stiffness.[9, 10] To overcome these limitations, additional measurements have been proposed, including the evaluation of pulmonary venous velocity, M-mode echocardiography flow velocity curves, and altering pre- and afterload conditions (Vasalva maneuver or nitroglycerin administration).[22, 23] In the current study however, these measurements were not performed as this study was only performed to evaluate the feasibility of MDCT.

Additionally, it has been suggested to combine transmitral velocity and mitral septal tissue velocity measurements when evaluating diastolic heart function. Importantly, the combined assessment of transmitral velocity and mitral septal tissue velocity represents a better estimate of LV filling pressures as it is a normalization of LV filling gradient for filling LV volume.[8, 12, 13]

Mitral septal tissue velocity

Ommen and colleagues ([8] studied the clinical use of TDI for evaluation of diastolic LV function in 100 patients. Comparison between invasive LV filling pressures and combined assessment of early transmitral velocity and mitral septal tissue velocity showed improved correlation ($r=0.64$) as compared to transmitral velocity ($r=0.59$) or mitral septal tissue velocity ($r=0.36$) alone.[8] In addition, MRI has been compared to TDI for assessment of

tissue velocities.[12] Paelinck et al.[12] used phase-contrast MRI and Doppler echocardiography to measure transmitral and mitral septal tissue velocities in 18 patients with hypertrophic cardiomyopathy. Importantly, combined assessment of early transmitral velocity and mitral septal tissue velocity (E/Ea) showed a good correlation between Doppler echocardiography and MRI ($r=0.89$, $p<0.01$). Moreover, invasive measurements were well correlated to E/Ea derived from Doppler echocardiography ($r=0.85$, $p<0.01$) and MRI ($r=0.80$, $p<0.01$). Likewise, the current study reported good correlations for transmitral velocity (E/A, $r=0.87$, $p<0.01$) and E/Ea ($r=0.88$, $p<0.01$). Furthermore, both studies showed that mitral septal tissue velocity was slightly overestimated when compared to Doppler echocardiography. With Doppler echocardiography, tissue velocities are quantified using changes in Doppler signal over time. Doppler patterns are only displayed for the region of interest (sample volume), located at the basal septal mitral valve annulus. With MDCT however, tissue velocities are measured using a different region of interest; ranging from the basal septal mitral valve annulus to the apex. The different regions of interest may have caused a slight overestimation of tissue velocity using MDCT.

Diastolic left ventricular function

Good agreement for detection of diastolic dysfunction was found when compared to Doppler echocardiography. This represents an important finding as the assessment of diastolic dysfunction provides important diagnostic, therapeutic and prognostic information in patients with cardiovascular disease, and more specifically, in patients with coronary atherosclerosis.[1-6] Additionally, it has been shown that patients with coronary atherosclerosis and normal LV systolic function may already exhibit diastolic dysfunction.[24] Accordingly, additional post-processing for diastolic dysfunction may have the potential to enhance the clinical evaluation derived from cardiac CT, particularly in patients with evidence of coronary atherosclerosis but normal LV systolic function. Moreover, the feasibility of MDCT for assessment of diastolic function is of particular interest as the number of patients referred for noninvasive evaluation of known or suspected coronary atherosclerosis with MDCT imaging has increased substantially over the recent years. In these patients, retrospective gating represents the most commonly used approach for cardiac CT.[16] In a large multicenter observational study, including 21 university hospitals and 29 community hospitals, Hausleiter et al.[16] recently showed that retrospective electrocardiographic gating was still applied in 94% of the 1965 enrolled patients. Importantly, in patients imaged with retrospective gating evaluation of diastolic LV function provides important additional information without additional radiation exposure.

Limitations

Some limitations need to be considered. At first, transmitral velocity parameters were assessed with Doppler echocardiography and MDCT as a noninvasive alternative to directly

measured LV filling pressures. Although direct measurements of LV filling pressures would have been preferred, they are not ideal for routine clinical examination. In addition, the assessment of LV filling pressures was performed by measuring early diastolic mitral septal tissue velocity with color-coded TDI. This technology provides lower values of tissue velocities as compared to pulsed-wave TDI.[25] Second, patients with valvular regurgitation were excluded. Severe valvular regurgitation may disturb accurate velocity measurements, leading to an inaccurate diastolic LV function analysis. Additional studies are needed to evaluate this potential confounding effect. Finally, one has to take into consideration that the effect of intravenous infusion of contrast media for cardiac CT angiography imaging on diastolic function indices is currently unknown.

Conclusions

Good correlations were observed for transmitral velocity, mitral septal tissue velocity and estimation of LV filling pressures when compared to 2D echocardiography using TDI. Moreover, a good agreement was found for detection of diastolic dysfunction using MDCT. Accordingly, MDCT is a feasible technique for assessment of diastolic function.

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