Three-dimensional echocardiography for left ventricular quantification in heart failure

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Quantification of left ventricular volumes and ejection fraction using freehand transthoracic three-dimensional echocardiography: comparison with magnetic resonance imaging.

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Abstract

Objectives: Our aim was to validate three-dimensional echocardiography (3DE) for assessment of left ventricular (LV) end-diastolic volume, end-systolic volume (ESV), stroke volume, and ejection fraction (EF) using the freehand-acquisition method. Furthermore, LV volumes by breath-hold versus free-breathing 3DE acquisition were assessed and compared with magnetic resonance imaging (MRI).

Methods: From the apical position, a fan-like 3DE image was acquired during free breathing and another, thereafter, during breath-hold. In 27 patients, 28 breath-hold- and 24 free-breathing 3DE images were acquired. A total of 17 patients underwent both MRI and 3DE. MRI contours were traced along the outer endocardial contour, including trabeculae, and along the inner endocardial contour, excluding trabeculae, from the LV volume.

Results: All 28 (100%) breath-hold- and 86% of free-breathing 3DE acquisitions could be analyzed. Intra-observer variation (percentual bias ± 2 SD) of end-diastolic volume, ESV, stroke volume, and EF for breath-hold 3DE was, respectively, 0,3 ± 10,2%, 0,3 ± 14,6%, 0,1 ± 18,4%, and –0,1 ± 5,8%. For free-breathing 3DE, findings were similar. A significantly better interobserver variability, however, was observed for breath-hold 3DE for ESV and EF. Comparison of breath-hold 3DE with MRI inner contour showed for end-diastolic volume, ESV, stroke volume, and EF, a percentual bias (± 2 SD) of, respectively, -13,5 ± 26,9%, -17,7 ± 47,8%, -10,6 ± 43,6%, and –1,8 ± 11,6%. Compared with the MRI outer contour, a significantly greater difference was observed, except for EF.

Conclusions: 3DE using the freehand method is fast and highly reproducible for (serial) LV volume and EF measurement, and, hence, ideally suited for clinical decision making and trials. Breath-hold 3DE is superior to free-breathing 3DE regarding image quality and reproducibility. Compared with MRI, 3DE underestimates LV volumes, but not EF, which is mainly explained by differences in endocardial contour tracing by MRI (outer contour) and 3DE (inner contour) of the trabecularized endocardium. Underestimation is reduced when breath-hold 3DE is compared with inner contour analysis of the MRI dataset.

Introduction

Accurate quantification of left ventricular (LV) volume and ejection fraction (EF) has important diagnostic, prognostic, and therapeutic implications. Several reports have shown that three-dimensional echocardiography (3DE) is far superior to conventional 2-dimensional echocardiography (2DE) [1-3]. Volumetry by 2DE, either by single-plane or biplane Simpson's rule, depends on geometric assumptions and is subject to image plane-positioning errors, [4-6] hence, it is not accurate in LV volumes that are distorted in shape, eg, after myocardial infarction [1-3]. 3DE has evolved during the last years from non-real-time techniques, with various methods of acquisition, to real-time 3DE. All these modalities have their advantages and limitations. The objective of this study was to evaluate the reproducibility of a new, non-real-time, freehand, fan-like acquisition method for 3DE (compact 3D cardiac imaging system, TomTec, Munich, Germany). Furthermore, LV volumes and EF measurements were compared with magnetic resonance imaging (MRI), and 3DE findings in this study were also compared with the 3DE literature. Finally, differences between breath-hold versus free-breathing-3DE acquisition (ie, respiratory gated) were evaluated.

Methods

Study population

Of the 32 patients studied initially, 27 had satisfactory image quality and a suitable apical acoustic window with second harmonic imaging. These patients could be included in the study after informed consent, according to guidelines of the institutional review board. Of these 27 patients, 2 were studied twice (postinfarct), yielding a total number of 29 3DE studies. Of the 27 patients, 16 were studied after myocardial infarction (in total 18 studies), of whom 6 had an apical aneurysm. One patient had hypertrophic cardiomyopathy, 2 patients had moderate aortic regurgitation, and 1 patient had severe mitral regurgitation (Barlow's disease). Furthermore, 7 healthy volunteers participated in the study (study population total 21 men and 6 women; mean age 50,2 ± 19,5 years).

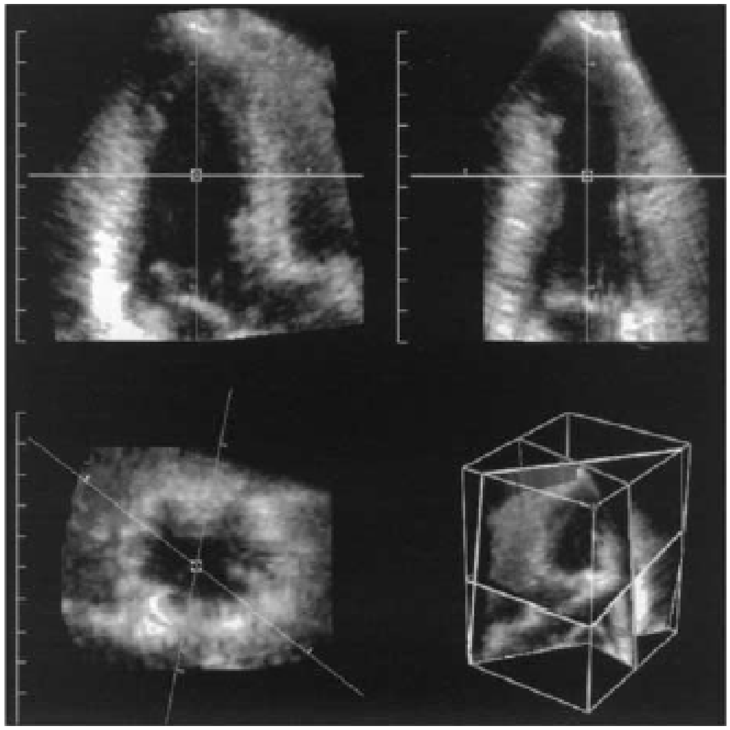
3DE image acquisition

An ultrasound machine (ATL HDI 5000, Philips Medical Systems, Eindhoven, The Netherlands) was used in gray scale, second harmonic-imaging (harmonic penetration) mode with a P4 transducer. The electromagnetic spatial locator was attached to the transducer and interfaced with the compact 3D cardiac imaging system (Tomtec). This 3DE acquisition system will be further referred to as the freehand method.

3DE image acquisition was performed in left recumbent position from an apical or para-apical window. Starting from an apical 4-chamber view, the operator tilted the ultrasound transducer slowly across the heart in a fan-like manner, toward the anterior or posterior wall, encompassing the entire LV volume by collecting 60 to 80 2-dimensional slices with 1 full cardiac cycle, which were digitally stored. The computer beeped for every accepted cardiac cycle, informing the operator about progress of the scan, and guiding the operator to proceed with tilting the transducer. On reaching the anterior or posterior epicardium, acquisition was temporarily suspended and the transducer was moved backward toward the 4-chamber view, again. Then acquisition was resumed and the transducer was slowly moved to the opposite side. The patient was instructed not to move during acquisition. If necessary, during acquisition (after a pause), it was allowed to displace the transducer one intercostal space, without compromising final 3D image quality. The acquisition and workstation acquires 2DE video information with frame rates of 25 to 50 Hz (Echoscan 4.2 software, Tomtec). An electromagnetic locator system (Flock of Birds, Ascension Technology Corp, Burlington, Vt) was transferring information about 3D spatial orientation of the echocardiography transducer to the computer, facilitating designation of spatial cartesian coordinates to every frame (the resolution/ accuracy of the locator system: translation accuracy is 0,18 cm root mean square (RMS); orientation accuracy is 0,5 degrees RMS). Electrocardiography (ECG) and respiratory triggering enables the system to compensate for changes in the cardiac cycle and to neglect images acquired during inspiration and during beats with R-R intervals that are outside preset limits (variability within 150 ms). During 3DE acquisition, the algorithm combined input from the video port and locator system and stored images according to their spatial orientation on hard disk. Respiratory gating was switched off during breath-hold acquisitions, in which 5 to 8 series of 10 to 12 heartbeats during suspended respiration (either inhalation or expiration) were acquired, with enough time between each series to allow the patient to gain breath.

Typically, both breath-hold and free-breathing acquisitions were performed within 3 minutes (on average 2,33 ± 0,55; range 1,5 - 3 minutes).

Figure 1



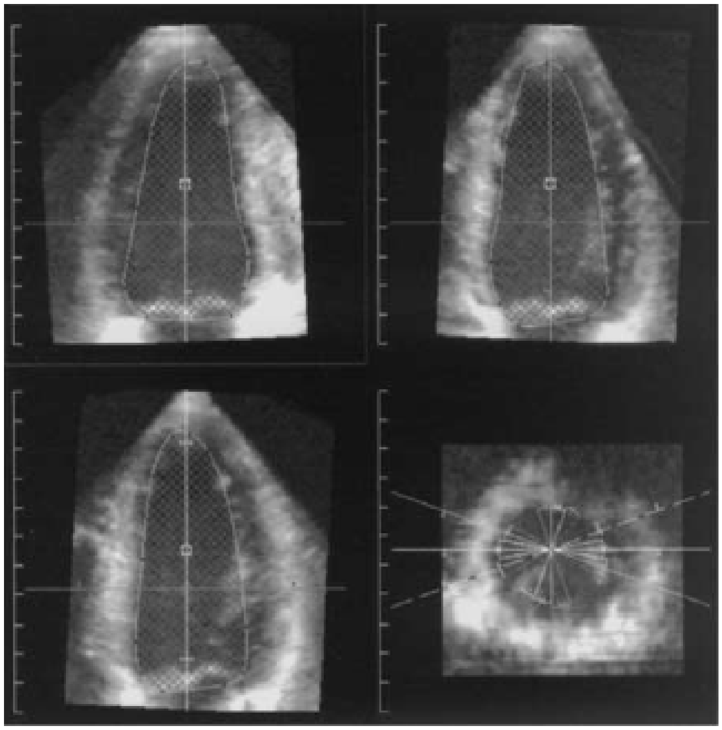
Four tile image continuous loop-display window is shown on analysis screen of workstation. Upper panels show 2 long-axis cross sections (respectively, 3- and 2-chamber view). Bottom left panel shows short-axis cross section. Bottom right tile is cubical display of entire three-dimensional dataset, transected by different cut planes, which make up other 3 panels.

Postprocessing and analysis

Offline, the images were postprocessed on the same workstation using software (Echoview 4.2, Tomtec), in about 3 to 5 minutes, depending on the size of the raw computer file. This resulted in a 4-tile image display screen (figure 1). After the optimal long axis was found, volume analysis was performed by the average rotation method with 9 slices centered on the true long axis rotated by 20 degrees each (interactive spline algorithm) [7,8]. The operator manually traced the inner contour of the endocardial border in every cut plane, both in end-systole and -diastole, with a possibility to click back and forth between frames for better appreciation of the endocardial motion. The traced areas of the end-diastolic and

-systolic frames of the long-axis slices were represented as pie slices in short-axis slices from base to apex; hence, each short-axis level could be examined (figure 2).

Figure 2



Average rotation method with 4 tile image-display window is shown on analysis screen of workstation. Upper panels and lower left panel show end-diastolic left ventricular long-axis cross sections, rotated with angle of 20 degrees relative to each other. Bottom right panel shows short-axis cross section at level of horizontal line in longaxis images, composed of 18 pie slices and transected by 9 cut lines, by which long-axis slices are defined. From base to apex, traced endocardial boundaries in long axis are represented by pie slices in corresponding short axis.

LV volumes and EF were automatically calculated by the computer. Adjustments in traced contours of short- and long-axis slices could easily be made. In this algorithm, papillary muscles (unless they blended in with the myocardium) and the mitral valve were completely included within the LV cavity. The valve planes were dealt with as is shown in figure 2. In each plane the 2 points of the mitral and aortic annulus were connected by a straight line. The entire analysis required about 20 to 30 minutes.

MRI

MRI was performed on a 1,0 Tesla scanner (the Impact Expert) in 2 patients, and a 1,5 Tesla scanner (the Vision) in 13 patients, and on the Sonata (also 1,5 T) in 2 patients (all made by Siemens Medical Systems, Erlangen, Germany). All patients were scanned in supine position using a 4-element, phased-array cardiac coil and prospective cardiac triggering. Cineimages, using a segmented gradient echo sequence, were acquired in 3 long-axis views (2-, 3-, and 4-chamber view) and in multiple short-axis views, every 10 mm, covering the whole LV. Sequence parameters were: effective repetition time/echo time (TR/TE) 45/6,1 ms, typical voxel size 2,0 x 1,3 x 6 mm (Impact [Siemens]); and effective TR/TE 40/4,8 ms, typical voxel size 1,9 x 1,3 x 6 mm (Vision [Siemens]). In the 2 patients scanned on the Sonata (Siemens) a steady state free precession gradient-echo sequence was used (True- Fisp, Siemens) with the following settings: TR/TE 34,8/1,6 ms, typical voxel size 1,4 x 1,3 x 5 mm. The short-axis cineimages were processed using a software package (Mass, Medis, Leiden, The Netherlands) loaded on a Sun Sparc station (Sun Microsystems, Mountain View, California, USA) to calculate LV volumes and EF. Endocardial contours were manually traced. The endocardial contour was drawn twice, including and excluding the trabeculae from the LV volume. This resulted in 2 sets of volumes and EF: MRI outer and inner contours. Papillary muscles were included in the LV cavity, unless they blended in with the myocardium. LV volumes were calculated by summation of the product (area x slice distance) of all slices.

LV length/width and volume measurements in 3DE and MRI datasets

To anticipate possible discrepancies between MRI outer contour and 3DE volumes, the LV end-diastolic and -systolic major length axis, from the center of the mitral annular plane to the epicardial apex, was measured offline in the 4-chamber view. Similarly, the largest LV width in 2-, 3-, and 4-chamber views between endocardial borders was measured for both techniques. Furthermore, the resulting volumes and EF of MRI inner and outer contours were compared with both breath-hold and free-breathing -3DE data.

Intraobserver and interobserver variability

One observer analyzed the 3DE images once, blinded to the results of the second observer. A second observer analyzed the 3DE images twice, with a 5-week interval, blinded for the results of the first analysis. Both observers were blinded to results of MRI measurements.

Statistical analysis

Percentual intraobserver and interobserver variability was expressed relative to the average volume as bias ± 2 SD by Bland-Altman analysis. For analysis of agreement of 3DE with MRI, the first measurement of the first observer was compared with MRI measurements in a similar manner. A paired t test was applied to test for differences between MRI and 3DE volumes, and EF and LV length and width measurements. Furthermore, a linear correlation coefficient (r) was calculated for the comparison of volumes, EF, and length and width measurements between 3DE and MRI. Comparison of bias and 95% confidence limits with values reported in literature for EDV, ESV, and EF was tested by t distribution with n-2 degrees of freedom (independant sample t test). Concordance analysis (κ) was used to test choice of frames for end-diastolic volume (EDV) and end-systolic volume (ESV) analysis in the intraobserver and interobserver variability.

Results

A total of 28 breath-hold and 24 free-breathing 3DE images were obtained during the same examination. In one patient, no breath-hold acquisition was attempted. Five free-breathing acquisitions could not be obtained or analyzed because of bad image quality and lung artifacts, rib artifacts, or both. The success rate of breath-hold 3DE was, therefore, 100%, and of free-breathing, 86%. Of the 26 patients, 17 underwent both MRI and 3DE within 10 ± 37 (range 1-64) days.

Breath-hold versus free-breathing 3DE, and 3DE versus MRI

The average values for EDV, ESV, stroke volume, and EF for the breath-hold and free-breathing-3DE acquisitions are shown in table 1. They were obtained from the 17 patients, who also had an MRI. There was no significant difference between the 2 modes of 3DE acquisition. Comparison between the MRI outer and inner contour methods, on the other hand, showed highly significant differences for volumes ($p < 0,00007$), but not for EF. Only MRI outer contour volumes, but not EF, were statistically significantly different compared with breath-hold and free-breathing 3DE by paired t test (table 1).

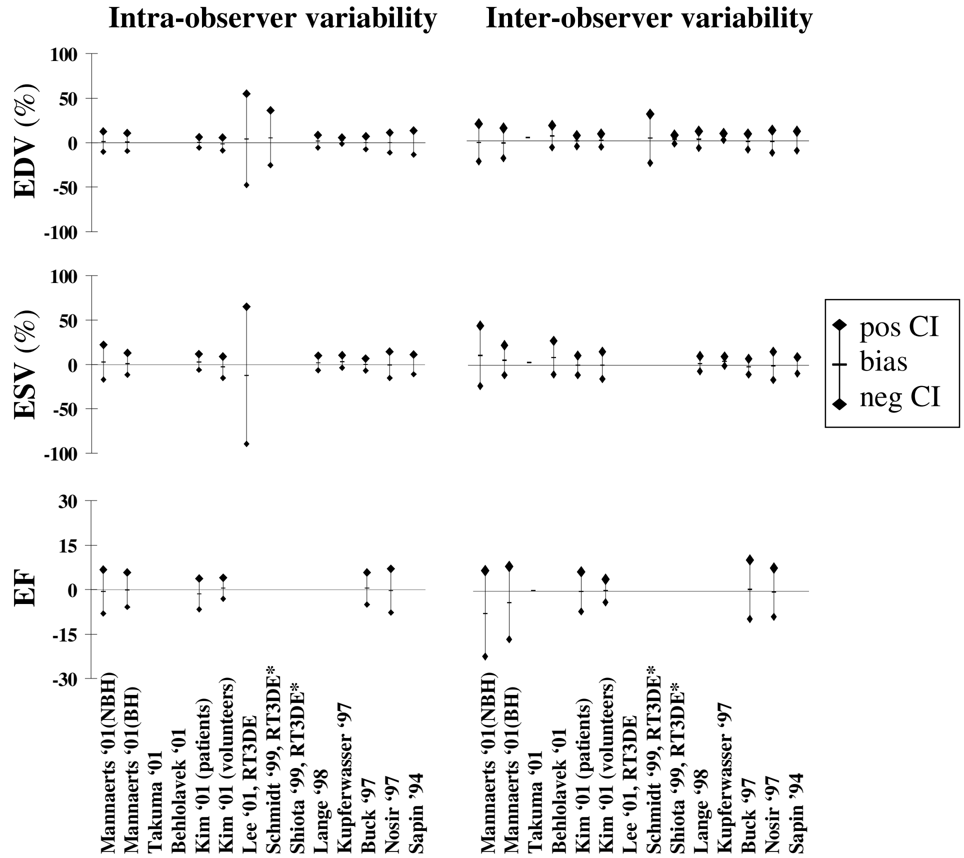
Table 1 Volumes and ejection fraction by three-dimensional echocardiography and magnetic resonance imaging (mL, mean ± SD)

	BH 3DE	FB 3DE	MRI inner contour	MRI outer contour	p, MRI outer contour vs BH / FB 3DE
EDV	100,6 ± 26,5	105,8 ± 31,7	115,2 ± 29,1	140,5 ± 40,3	0,003 / 0,02
ESV	40,8 ± 20,7	48,1 ± 23,5	48,7 ± 22,7	60,6 ± 28,5	0,03 / NS
SV	59,7 ± 17,7	57,8 ± 21,6	66,4 ± 20,2	79,7 ± 29,9	0,03 / 0,03
EF	60,3 ± 12,2	55,7 ± 13,7	58,4 ± 12,4	57,4 ± 13,6	NS / NS

Average values for end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF) by magnetic resonance imaging (MRI) and three-dimensional echocardiography (3DE) (matched examinations). N = 17 for breath-hold (BH) 3DE, N = 13 for free-breathing (FB) 3DE. N = 17 for MRI (inner and outer contour). P values for comparison between BH and FB 3DE and MRI outer contour are shown. There were no significant differences between MRI inner contour and the two 3DE modalities. p-values are shown. NS, not significant; SV, stroke volume.

Intraobserver and interobserver variation (percentual bias ± 2 SD) was derived from 28 breath-hold and 24 free-breathing-3DE images. For breath-hold, 3DE-based EDV, ESV, stroke volume, and EF, was, respectively, 0,3 ± 10,2%, 0,3 ± 14,6%, 0,1 ± 18,4%, and –0,1 ± 5,8%. For free-breathing 3DE these were, respectively, 0,8 ± 11,6%, 2,4 ± 20,0%, -0,1 ± 19,4%, and –0,7 ± 7,4%. Interobserver variation for breath-hold 3DE was for EDV, ESV, stroke volume, and EF, respectively, -2,0 ± 18,6%, 7,2 ± 20,6%, -9,5 ± 40,4%, and –3,9 ± 12,2%. For free-breathing 3DE these were, respectively, (bias ± 2SD) –1,7 ± 19,8%, 16,4 ± 41,8%, -14,9 ± 33,0%, and –7,5 ± 14,4%. In figure 3 the bias and 95% confidence limits for percentual EDV, ESV, and EF of this study were compared with those reported in the literature. A significantly smaller interobserver variability was observed for breath-hold versus free-breathing 3DE for ESV ($p < 0,034$), and EF ($p < 0,002$). All other comparisons in figure 3 were not significantly different. Concordance in frame choice for intraobserver and interobserver measurements was high (respectively, a κ value of 0,73 and 0,59).

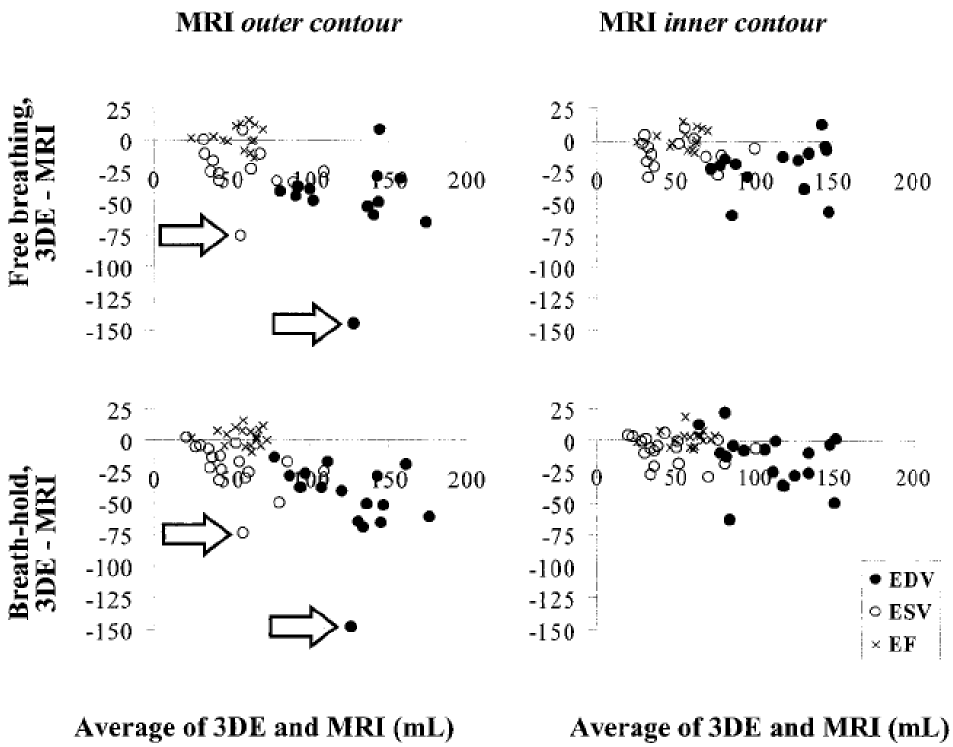
Figure 3



Bland-Altman plot showing percentual intraobserver/interobserver variability. On x axis several authors, who have used three-dimensional echocardiography (3DE) in clinical settings, are shown together with year of publication. On y axis percentual bias (short horizontal bars) and 95% confidence intervals (CI) are indicated (connected by diamonds) for end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF). Authors Schmidt and Shiota grouped together ESV and EDV. Volumes are arbitrary compared with other EDV volumes. Shiota only showed interobserver variability. Takuma only reported bias without CI. FB, free-breathing acquisitions; BH, breath-holding acquisitions, RT, real-time.

Figure 4 shows Bland-Altman plots for comparison between breath-hold and free-breathing 3DE and MRI inner and outer contour (absolute values in mL). Table 2 shows the percentual bias ± 2 SD for the relation between breath-hold 3DE versus MRI inner and outer contour and free-breathing 3DE versus both MRI analysis methods. Furthermore, the corresponding r are given.

Figure 4



Bland-Altman analysis between left ventricular volumes (mL) measured by three-dimensional echocardiography (3DE) and magnetic resonance imaging (MRI). Breath-hold and free-breathing 3DE is compared with MRI inner and outer contour in corresponding panels. Large arrows indicate outliers for end-systolic volume (ESV) and end-diastolic volume (EDV) in single patient with hypertrophic cardiomyopathy, whose MRI was obtained with a Sonata scanner and analyzed by outer contour method. Closed circles, EDV; open circles, ESV; cross marks, EF.

Table 2 Comparison between 2 three-dimensional echocardiography techniques with 2 methods of magnetic resonance imaging analysis (percentual bias ± 2 SD)

	Breath-hold 3DE minus MRI inner contour	Breath-hold 3DE minus MRI outer contour	Free-breathing 3DE minus MRI inner contour	Free-breathing 3DE minus MRI outer contour
EDV	-13,5 ± 26,9	-27,9 ± 45,7	-17,1 ± 31,0	-39,0 ± 36,7
ESV	-17,7 ± 47,8	-34,4 ± 45,5	-17,3 ± 42,3	-41,7 ± 61,3
SV	-10,6 ± 43,6	-22,4 ± 54,8	-13,8 ± 33,5	-36,4 ± 53,5
EF	-1,8 ± 11,6	2,8 ± 13,7	1,2 ± 15,8	1,3 ± 17,7
EDV *r*	0,74	0,79	0,92	0,82
ESV *r*	0,88	0,90	0,93	0,88
SV *r*	0,74	0,74	0,88	0,78
EF *r*	0,89	0,87	0,84	0,80

Bland-Altman analysis for the comparison between three-dimensional echocardiography (3DE) modalities and magnetic resonance imaging (MRI) modalities. *r*, correlation coefficients corresponding to the 3DE and MRI modalities used in each column. Abbreviations: EDV, End-diastolic volume; ESV, end-systolic volume; SV, stroke volume; EF, ejection fraction.

The length and width measurements of the LV volumes by breath-hold 3DE and MRI outer contour for 2-, 3-, and 4-chamber views are shown in table 3. LV length measurements were not significantly different between 3DE and MRI outer contour. In contrast, difference in width measurements reached a high level of significance ($p < 0{,}008$). The r values between the end-diastolic lengths for 3DE and MRI outer were 0,82 and, for the end-systolic lengths, 0,75.

Table 3 Comparison between left-ventricular length and width measurements for breath-hold three-dimensional echocardiography and magnetic resonance imaging outer contour

	End-diastolic					
View	4CV		3CV		2CV	
Technique	3DE	MRI	3DE	MRI	3DE	MRI
LV length	101,4 ± 9,2	101,0 ± 8,1				
LV width	43,0 ± 7,5	49,0 ± 6,7	39,4 ± 8,0	50,1 ± 5,3	36,7 ± 9,4	54,4 ± 3,6

	End-systolic					
View	4CV		3CV		2CV	
Technique	3DE	MRI	3DE	MRI	3DE	MRI
LV length	91,0 ± 8,8	91,9 ± 8,4				
LV width	29,9 ± 8,2	37,3 ± 4,8	27,1 ± 6,6	35,5 ± 5,3	26,4 ± 7,8	38,0 ± 3,9

Abbreviations: LV, Left ventricular; 3DE, three-dimensional echocardiography; MRI, magnetic resonance imaging; CV, chamber view. Mean length and width (average ± SD, in mm) are shown for 17 paired observations with breath-hold 3DE and MRI outer.

Discussion

Various 3DE modalities have been developed for LV volume assessment during the last 10 years, which have all been validated against several other techniques such as MRI [1,9-16], cineventriculography [1,14,17-19], multigated radionuclide angiography [12,14,20,21] and electron-beam tomography [22] or (balloon) phantoms [23-26]. There was, in general, a good correlation with other non-invasive techniques and phantoms for LV volumes and EF. Initially, 3DE techniques were compared with 2-dimensional volumetry using single-plane or biplane Simpson's rule [1,5,10,17,20,27]. Compared with 2DE, the intraobserver/interobserver variability significantly improved (2- to 3-fold) by 3DE [1,10,17,20].

Intraobserver and interobserver variability of breath-hold and free-breathing acquisitions in relation to other 3D studies

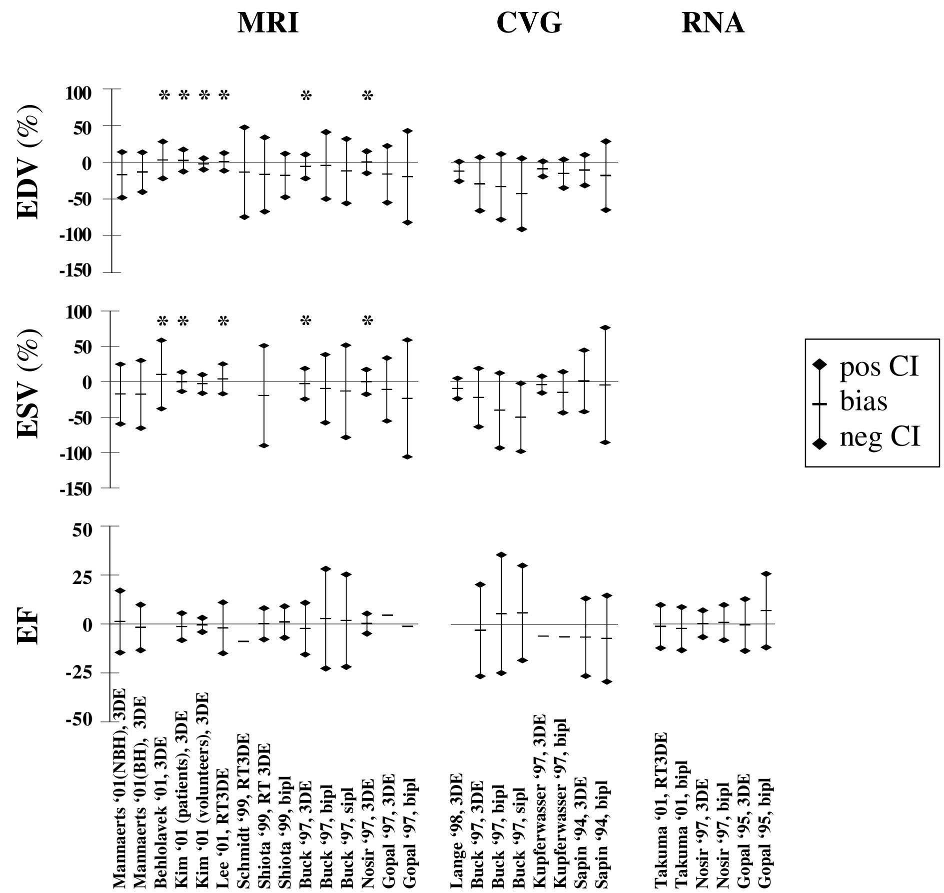
Intraobserver variability and bias for breath-hold and free-breathing 3DE were small and in line with the literature (figure 3). For intraobserver variability there were no significant differences between the 2 modes of 3DE acquisition, whereas for the interobserver variability, ESV and EF, but not EDV, had a significantly better reproducibility in the breath-hold acquisitions (figure 3). As expected, interobserver variability was more pronounced (although still in line with the literature) than intraobserver variability for both methods of acquisition. The differences in interobserver variability for ESV and EF between the free-breathing and breath-hold acquisition may be caused by 3 important factors: a better image quality in the inspiratory or expiratory breath-hold acquisitions as a result of disappearance of tissue interposition of rib or lung tissue; a systematic difference in interpretation of the endocardial border; and the smaller ESVs, which are more affected by extracardiac (respiratory) motion changes, in spite of respiratory gating. Especially in the ESVs from the free-breathing acquisitions, the diaphragmatic motion during the entire expiration, where beats are acquired, will result in some blurring with subsequent loss of endocardial definition and reproducibility. Although the respiratory phase window of the respiratory gating algorithm can be adjusted, it is impractical to make it too small, because acquisition time will become unacceptably long. This imperfection of the respiratory gating is eliminated if it is switched off during breath-hold acquisitions.

Comparison with other methods for volumetry

Figure 5 shows the comparison of MRI data for EDV, ESV, and EF hitherto published by several authors, including our findings, with both breath-hold and free-breathing 3DE. It is evident that almost all 3DE studies, including this study, tended to underestimate both EDV and ESV, but not EF relative to MRI (table 2 and figure 5).

Percentual bias and confidence limits in this study for EDV, ESV, and EF were generally in the range of data reported by others [10,13,16,27]. On the other hand, significantly smaller underestimation and confidence limits have also been reported for EDV and ESV, but not for EF, as shown in figure 5 [9,11,13,28]. Patient populations were different between studies in terms of LV volumes, presence of aneurysms, image quality of 3DE and MRI, endocardial contour tracing of both the 3DE and MRI images (outer vs inner contour), and number of patients. The 2 former factors are probably not going to have a profound effect, because these are the same for MRI and 3DE. The latter 3, however, are likely to have an important effect on the results, especially on the width of the 95% confidence limits.

Figure 5



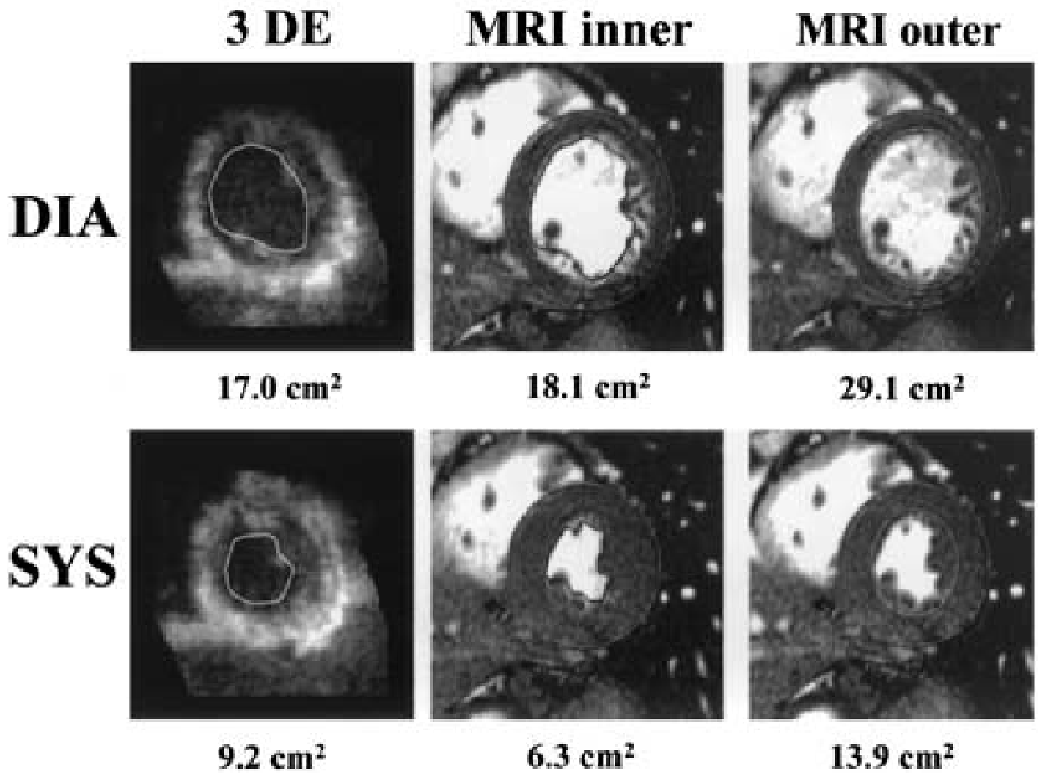
Bland-Altman plot showing comparison of three-dimensional echocardiography (3DE) studies together with year of publication (x axis) to magnetic resonance imaging (MRI), left ventricular cineventriculography (CVG), and radionuclide angiography (RNA). Percentual bias (short horizontal bars) and 95% confidence intervals (CI) are indicated (connected by diamonds) for end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF). Belohlavek is grouped together with MRI results, but compared 3DE with electron-beam computed tomography. * Shows significant differences for EDV and ESV relative to values of Mannaerts' breath-holding (BH) acquisition 3DE (compared with MRI inner contour; for EF there were no significant differences); bipl, biplane 2-dimensional echocardiography (2DE); sipl, single-plane 2DE (which were obtained in the same studies); RT, real-time; FB, free-breathing acquisition.

It is not always apparent from the literature mentioned as to how the endocardium was traced during MRI analysis (inner or outer endocardial contour), which hampers comparison between MRI and 3DE. Currently, the outer contour method is usually used in MRI analysis, because this allows better assessment of systolic wall thickening. There are several possible explanations for the discrepancy in LV volumes as assessed by MRI and 3DE. In our opinion a few are of major importance. These are tracing of the sponge-like inner or outer endocardial contour by, respectively, 3DE and MRI, and variable end-slice positioning by MRI.29 The former is supported by table 3, which clearly shows that the major long axis in the 4-chamber view for MRI outer contour and breath-hold 3DE are similar, in contrast to the maximal width in the 2-, 3-, and 4-chamber views, and, furthermore, the volumes for MRI inner contour were significantly smaller than for MRI outer contour. For EF these volume effects were canceled out.

In the latest MRI equipment, acquisition with pulse sequences with steady-state free precession yield a very high contrast between blood and endocardium, which accentuates the trabeculae even more and, therefore, could potentially produce even larger volumes relative to 3DE if the MRI outer contour analysis is used. The largest volume underestimation for 3DE was observed in the 2 patients scanned by the Sonata (Siemens) scanner (figures 4 and 6). Foreshortening or exclusion of a part of the LV volume out of the 3D dataset did not occur in this study, because this can be checked in the cubical display of the 3D dataset by reconstructing the major length axis.

The freehand system used in this study generated a pyramidal 3D dataset with a top angle of approximately 90 to 130 degrees and, therefore, the largest top angle and 3D dataset of all the available 3DE systems (theoretically a sweep angle of 130 degrees in a pyramidal dataset, with a sector angle of 90 degrees, yields a 1,74 times larger volume compared with a conical dataset with a 90-degree top angle). This is in contrast to the first generation real-time 3DE systems, which generate pyramidal 3D datasets with a small top angle of 64 degrees [9,16,27]. In the latter, volume underestimation may become important in the case of dilated or aneurysmatic ventricles. Furthermore, as a result of the sparse array configuration of these scanners, resolution is relatively poor, with especially large confidence limits as a result. Cineventriculography overestimated in all studies the LV volumes, relative to 3DE as a result of its geometric assumptions, and the outer contour of trabecularized LV endocardium being traced, rather than the inner contour by 3DE [30].

Figure 6



Example of patient with moderate aortic regurgitation. Short-axis cross section at papillary muscle level is shown in end-diastole (DIA, top panels) and end-systole (SYS, bottom panels). Two left panels are breath-hold three-dimensional echocardiography (3DE) images. Middle and right panels are magnetic resonance imaging (MRI) obtained by the Sonata scanner and analyzed by the inner and outer contour methods, respectively. Effects on short-axis areas are evident. Note relative lack of trabecularization in 3DE images.

Advantages of the freehand method

The freehand equipment can be used in conjunction with any echocardiography machine. This versatility is an advantage for centers that do not wish to dedicate one echocardiography machine exclusively to 3DE. In our experience 3DE with the freehand method can be performed quickly (with an acquisition time less than 3 minutes), and easily by an (para-) apical acquisition with a fan-like sweep encompassing the entire LV volume. The acquisition can be interrupted to reposition the transducer one intercostal space without compromising final image quality after postprocessing. The latter is not possible with the rotational acquisition method [23].

Limitations to the freehand method

The term “freehand acquisition” suggests a versatile acquisition from any acoustic window that, after postprocessing, ideally would yield a complete dynamic 3D dataset of good quality. Unfortunately, however, in our experience such a multiwindow acquisition of good quality is not possible if the windows are too far apart (eg, parasternal and apical). ECG triggering is a limitation to all nonrealtime methods. In case of irregular rhythms or atrial fibrillation, the acquisition time will be markedly prolonged and image quality will deteriorate. Care has to be taken that the R-R limits are not set too broadly, because this will lead to a shortened and incomplete cardiac cycle (with loss of a true endsystolic frame), especially with higher heart rates. Another limitation of the freehand system is that it is video-based, instead of using the raw digital data output. The latter will yield superior image quality and much higher frame rates compared with the video frame rate of 25 to 50 frames/s.

Clinical implications

The freehand method is a clinically feasible, nonrealtime method with a fast and easy acquisition, which can be easily adapted to all commercially available 2-dimensional ultrasound machines. With the use of multiple breath-holds the reproducibility for LV volumes and EF is good and comparable with other 3DE techniques. Of all current 3DE methods, the freehand method has the potential to generate the largest 3D datasets, which avoids volume underestimation in dilated or aneurysmatic hearts. These characteristics makes it a very useful tool for serial follow-up, eg, after myocardial infarction or congestive heart failure. For comparison of 3DE with MRI for LV volumetry, it is mandatory to clearly indicate whether the inner or outer endocardial contour is traced in the MRI volume measurements, and which pulse sequences and MRI equipment are used.

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