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ORIGINAL PAPER

Single-beat real-time three-dimensional echocardiographic automated contour detection for quantification of left ventricular volumes and systolic function

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Abstract To assess the feasibility and accuracy in measuring left ventricular (LV) end-diastolic volume (EDV), end-systolic volume (ESV) and ejection fraction (EF) with Siemens single-beat real-time 3D transthoracic echocardiography. The LV volumes and EF were measured in 3D datasets acquired by six imaging modes (time-1-harmonic (T1H), time-1-fundamental, time-2-harmonic, time-2-fundamental, space-1-harmonic (S1H), and space-1-fundamental) in 41 patients using the automated contouring algorithm and compared with manually corrected 3DE QLAB measurements. The main determinates of the temporal and spatial resolutions of 3D datasets acquired were the fundamental and harmonic modes. Consequently, the S1H mode had the lowest volume rate and highest spatial resolution. Compared with the 3DE QLAB analysis, the S1H mode resulted in the best LV volumes and EF estimates in all patients (0 ± 10 % for EF, -7 ± 44 ml for EDV, -7 ± 39 ml for ESV) and in the 10 patients with correct LV contour tracking according to a visual assessment from the multiplanar reconstruction views in all six modes (0 ± 9 % for EF, -3 ± 23 ml for EDV, -2 ± 14 ml for ESV). The T1H mode was the best alternative. Overall 28 patients (68 %) could be analysed automatically and satisfyingly with the S1H and T1H modes: 0 ± 8 % (EF), 0 ± 27 ml (EDV) and -1 ± 16 ml (ESV). The accuracy of the Siemens automated RT-3D algorithm in measuring LV volumes and EF is significantly influenced by the different imaging modes. The S1H mode may be the preferred 3D acquisition mode, supplemented by the T1H mode in enlarged LVs that do not fit in the S1H acquisition sector.

Keywords Left ventricle · Three-dimensional · Echocardiography

Left ventricular (LV) volumes and ejection fraction (EF) are the most used parameters in assessing LV function and have important prognostic significance [1, 2]. To assess these parameters, echocardiography is the most commonly applied imaging modality in routine clinical practice. Three-dimensional transthoracic echocardiography (3DE) has been considered as the optimal echocardiographic technique, mainly because of the absence of geometric assumptions. Although the accuracy of 3DE has been validated against cardiac magnetic resonance (CMR) imaging [3–8], it is still limited by the use of stitched LV subvolumes [3, 4, 7] and semiautomatic contouring of the endocardial border that may result in time-consumption and less reproducible data analysis [5, 6, 9, 10]. Single-beat full volume real-time 3D transthoracic echocardiography (RT-3DE) is a new imaging technique capable in acquiring the LV from a single heartbeat and also allows fully automated contouring of the 3D LV endocardial surface. This imaging modality has been validated recently in different patient populations [11, 12]. However, several acquisition imaging modes of the RT-3DE are available with significant differences in temporal and spatial resolutions of 3D datasets acquired. In this study we sought to assess the feasibility and accuracy in measuring LV volumes and EF in the different harmonic and fundamental imaging modes of the RT-3DE.

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Patients and methods

Study population

Consecutive patients with sinus rhythm and non-hypertrophied LV scheduled for a routine echocardiographic examination for various indications were enrolled prospectively. Patients with severely distorted LV and inferior image quality were excluded from the study. All patients had undergone 3DE with the iE33 xMatrix ultrasound system (Philips Medical System) and RT-3DE with the Acuson SC2000 ultrasound system (Siemens Ultrasound). The protocols were approved by the institutional review board and informed consent was obtained from all patients.

3D transthoracic echocardiographic image acquisition and analysis

3DE was performed using the iE33 xMatrix ultrasound system (Philips Medical System) with the X5 transducer. Electrocardiographically gated full volume datasets of the LV (each built from four subvolumes) were acquired from the apical window during breath-hold with proper gain and depth (11–14 cm) to optimize the volume rate. Care was taken to include the complete LV within the imaging volume throughout the acquisition by adjusting the lateral and elevation widths of the acquisition sector. Each full volume dataset was digitally stored and exported to QLAB 8.0 3DQA software (Philips Medical System) for offline analysis by a highly experienced blinded investigator (WBV). The full volume LV 3DE dataset was displayed as three orthogonal multiplanar reconstruction (MPR) views of the LV. After selecting the end-diastolic (ED) and end-systolic (ES) reference frames, five reference points (four on the mitral annulus and one on the LV apex) were added in two orthogonal MPR views of the reference frames. The software traced the LV endocardial border and calculated the volumes and EF automatically. The endocardial contours were corrected by the same investigator (WBV) manually if the QLAB automated contouring algorithm failed to trace the LV endocardium properly.

Single-beat full volume real-time 3D transthoracic echocardiographic image acquisition and analysis

The RT-3DE was performed using the Acuson SC2000 ultrasound system (Siemens Ultrasound) with the 4Z1c real-time full volume transducer. After the gain and depth (12–14 cm) were adjusted, real-time full volume datasets of LV were acquired in a single cardiac cycle from the apical window during breath-hold with six different imaging modes available: Time 1 Harmonic (T1H), Time 1 Fundamental (T1F), Time 2 Harmonic (T2H), Time 2 Fundamental (T2F), Space 1 Harmonic (S1H), and Space 1 Fundamental (S1F). The Space 2 modes were not used because the sector size was too small to include the complete LV. The maximum sector size of the T1H, T1F, T2H, T2F and S1F modes was 90° × 90° and that of the S1H modes was 69° × 66°. Care was taken to include the complete LV within the imaging volume throughout the acquisition. Each full volume RT-3DE dataset was digitally stored and exported to syngo SC2000 Workplace LV Analysis (Siemens Ultrasound). The offline analysis was done by an investigator (BR) blinded to the 3DE QLAB analysis. This custom algorithm traces the LV endocardial surface and selects the end-diastolic volume (EDV) from the electrocardiographic R-wave signal and the minimal systolic volume as the end-systolic volume (ESV) automatically. No manual corrections of the ED and ES frames and endocardial contour tracing were made. Three 2D MPR planes with the automated contour, the 3D mesh rendering of the LV cavity, as well as the LV volumes, EF measurements and volume-time curve were presented automatically (Fig. 1). The correctness of segmental motion of the automated 3D LV endocardial contours during the cardiac cycle of all six imaging modes was evaluated by the same observer (BR) in two MPR views (4-chamber and 2-chamber views) of the 3D datasets. If the LV endocardium was not seen clearly in the MPR views, the LV automated contour was accessed by comparing the contours with the 2D images of the transthoracic apical 4-chamber and 2-chamber views.

Statistical methods

All values were expressed as mean ± standard deviation and number (percentage). Linear regression analysis was used to assess the correlation of the EF, EDV and ESV between Siemens RT-3DE and 3DE QLAB measurements. Bland–Altman method in which differences were plotted against the 3DE QLAB measurements was used to assess the agreement between the two modalities. Differences were considered statistical significant when $p < 0.05$.

Results

Patient characteristics and feasibility of the Siemens RT-3DE

Initially, 48 patients were included. The Siemens RT-3DE automated contouring algorithm failed to trace the LV endocardium in datasets acquired by all six imaging modes in three patients because of false data-acquisition triggering and in four patients due to inferior image quality. Finally,

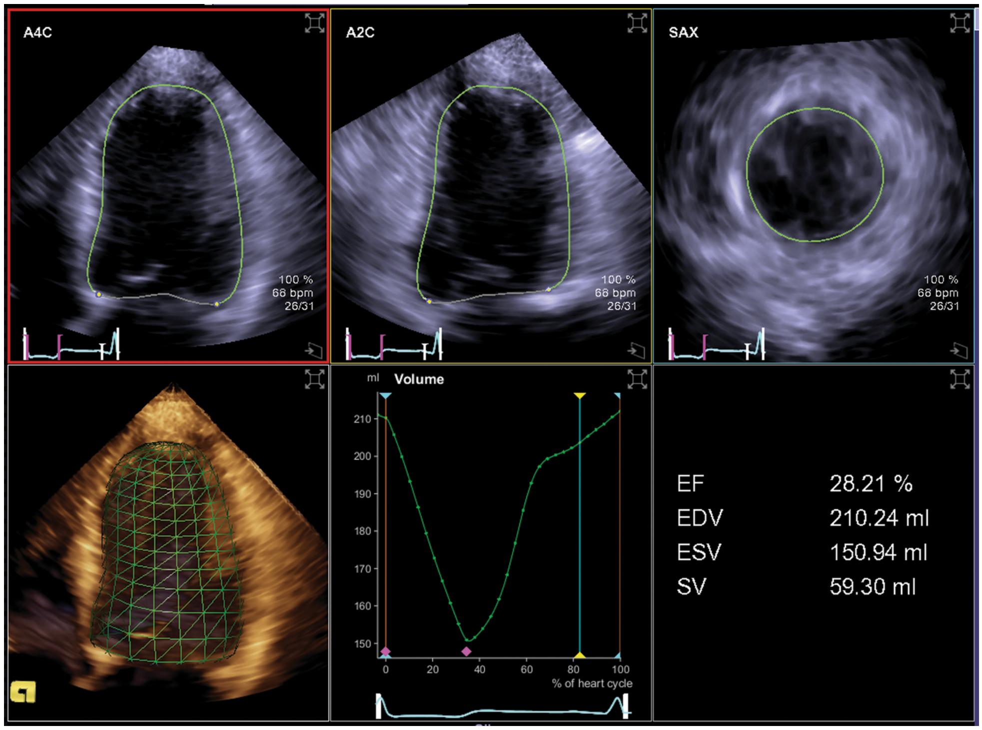

Fig. 1 The result page of the automated contouring algorithm of Siemens single-beat full volume real-time 3D transthoracic echocardiography including three 2D multiplanar reconstruction planes with the automated contour, the 3D mesh rendering of the left ventricular cavity, left ventricular volumes and ejection fraction measures and volume-time curve

41 patients were enrolled in the data analysis. The feasibility of the Siemens RT-3DE automated contouring algorithm in all patients included was therefore 85 %.

In the 41 patients, the mean age was 56 ± 17 years and 73 % were male. Most patients had degenerative valvular heart disease (39 %) or non-hypertrophic cardiomyopathy (46 %). The apical acquisition of one to two consecutive cardiac cycles of RT-3DE datasets took 3–5 s depending on the heart rate. The automated algorithm analysis required 25 ± 3 s for one cardiac cycle and 34 ± 4 s for two cardiac cycles depending on the imaging modes. In the 3DE QLAB analysis, the semiautomated LV contour was corrected manually in 40 patients (98 %), and the manual correction in each case required 10 ± 5 min.

Temporal and spatial resolutions of the imaging modes of the RT-3DE

The average volume rate of the Philips 3DE datasets was 26 ± 6 volume per second (vps) and that of Siemens RT-3DE datasets was 49 ± 7 vps (T2F), 34 ± 4 vps (T1F), 24 ± 4 vps (S1F), 24 ± 4 vps (T2H), 17 ± 2 vps (T1H) and 14 ± 2 vps (S1H). In addition, the spatial resolution was different in the different Siemens RT-3DE imaging modes. The Siemens RT-3DE images were generally smoother in visualizing the myocardial tissue in the Harmonic modes than that in the Fundamental modes (Fig. 2). According to the visualization of the cardiac structures and recognisability of the LV endocardial motion during the cardiac cycle, the 3D spatial resolution of the Space modes was better than that of the Time modes (Fig. 2).

Accuracy of the automated LV contouring algorithm of the RT-3DTTE with six different imaging settings

The comparisons of the LV volumes and EF between six imaging modes of the Siemens RT-3DE and the 3DE QLAB in all patients are shown in Table 1. The volumes and EF of all six imaging settings calculated by the automated algorithm correlated well with the 3DE QLAB measurements (all $p < 0.001$). Bias of the EF was positive in S1H mode and negative in all other imaging modes; biases of the EDV and ESV were negative in S1H mode and positive in all other imaging modes. The absolute bias values of EF, EDV and ESV from the S1H and T1H modes were smaller than those from the other modes.

Based on the visually assessed segmental motions of the LV contour during the cardiac cycle in the MPR views of the Siemens RT-3DE datasets, the automated LV contour was correct in all six imaging modes in 10

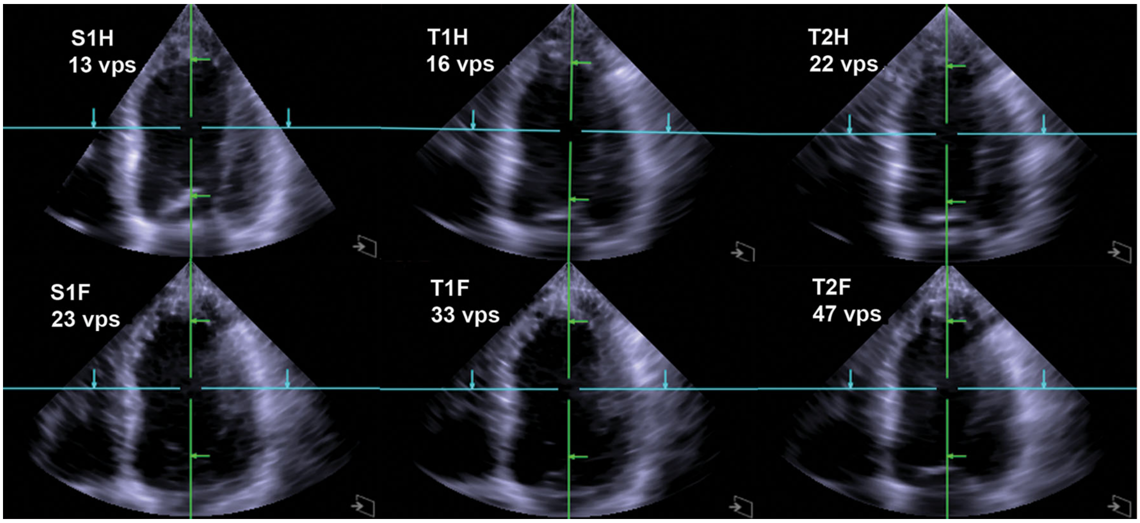

Fig. 2 Sample 3DE datasets acquired by the six imaging modes with different temporal and spatial resolutions of Siemens single-beat full volume real-time 3D transthoracic echocardiography. *S1H* Space 1 Harmonic, *T1H* Time 1 Harmonic, *T2H* Time 2 Harmonic, *S1F* Space 1 Fundamental, *T1F* Time 1 Fundamental, *T2F* Time 2 Fundamental

Table 1 Pearson correlation coefficient and Bland–Altman analysis of the EF and left ventricular volumes between six imaging modes of Siemens single-beat full volume real-time 3D transthoracic echocardiography (RT-3DE) and 3DE QLAB in all patients (n = 41)

	Siemens RT-3DE					
	T2F	T1F	S1F	T2H	T1H	S1H
EF (%)						
Pearson *r*	0.84	0.89	0.84	0.88	0.92	0.95
Bias	−7	−7	−6	−3	−1	0.4
Limits of agreement (2SD)	14	14	16	15	12	10
EDV (ml)						
Pearson *r*	0.88	0.91	0.88	0.93	0.91	0.92
Bias	21	20	21	11	6	−7
Limits of agreement(2SD)	40	46	46	42	46	44
ESV (ml)						
Pearson *r*	0.85	0.92	0.90	0.91	0.93	0.92
Bias	22	22	21	10	3	−7
Limits of agreement (2SD)	38	38	38	41	36	39

EF ejection fraction, *EDV* end diastolic volume, *ESV* end systolic volume, *SD* standard deviation; other abbreviations as in Fig. 2

patients (24 %). The comparisons of the EF and LV volumes between six imaging modes of the Siemens RT-3DE and the 3DE QLAB in these 10 patients are shown in Table 2. The EF, EDV and ESV of all six imaging settings calculated by the automated algorithm had excellent correlations with the 3DE QLAB measurements (all $p < 0.001$). Bias of the EF was positive in S1H and negative in other modes; bias of the EDV was negative in S1H and T1H modes and positive in other modes; bias of the ESV was negative in S1H modes and positive in other modes. The bias of the EF and limits of agreement of the EF and LV volumes were improved for all six imaging modes in these ten patients.

Use of the different imaging modes in routine clinical practice

Since the S1H mode led to the best results, this mode was selected as the primary imaging mode for potential use in routine clinical practice. In 23 patients (56 %), the LV cavity fitted completely in the acquisition sector and the automated LV contour tracking was, based on the visual assessment, correct. The comparisons of the EF and LV volumes of the S1H mode and the 3DE QLAB measurements in these 23 patients are depicted in Fig. 3a. Correlations between the S1H mode and 3DE QLAB were excellent for EF ($r = 0.95$), EDV ($r = 0.97$) and ESV

Table 2 Pearson correlation coefficient and Bland–Altman analysis of the EF and left ventricular volumes between six imaging modes of Siemens RT-3DE and 3DE QLAB in the patients with (as assessed visually) correct automatic contour tracing of the Siemens RT-3DE (n = 10)

	Siemens RT-3DE					
	T2F	T1F	S1F	T2H	T1H	S1H
EF (%)						
Pearson *r*	0.95	0.96	0.88	0.92	0.89	0.95
Bias	−7	−6	−5	−5	−2	0.4
Limits of agreement(2SD)	9	10	14	11	13	9
EDV (ml)						
Pearson *r*	0.96	0.94	0.92	0.90	0.95	0.96
Bias	14	17	22	10	−1	−3
Limits of agreement(2SD)	21	30	39	34	25	23
ESV (ml)						
Pearson *r*	0.99	0.99	0.99	0.97	0.98	0.99
Bias	16	17	19	11	1	−2
Limits of agreement(2SD)	13	14	15	20	18	14

Abbreviations as in Table 1

($r = 0.99$) (all $p < 0.001$), with biases and limits of agreement of 1 ± 9 % (EF), -2 ± 26 ml (EDV) and -3 ± 16 ml (ESV). In the eight patients in whom the LV cavity did not fit completely into the acquisition sector of the S1H mode, the automated contour tracking of the T1H mode as the best alternative was correct in five patients based on the visual assessment. Thus, overall 28 of 41 patients (68 %) could be analysed automatically and satisfyingly with the following results compared with the 3DE QLAB measurements (Fig. 3b): correlation coefficient $r = 0.95$ (EF), $r = 0.96$ (EDV) and $r = 0.98$ (ESV); biases ± limits of agreement 0 ± 8 % (EF), -0 ± 27 ml (EDV) and -1 ± 16 ml (ESV).

Discussion

This is the first study to assess the feasibility and accuracy of the Siemens RT-3DE automated algorithm in measuring the LV volumes and EF of 3D datasets acquired by the six different available imaging modes. The main finding of this study was that the accuracy of the automated algorithm was influenced significantly by the different imaging modes. Compared with the manually optimized 3DE QLAB measurements, the automated measurements of the S1H mode were superior particularly in terms of the bias, and to a less extend in correlation and limits of agreement.

The temporal resolution of the different imaging modes

The major determinant of the temporal resolution was the Fundamental versus the Harmonic modes, i.e. the temporal resolution of the Fundamental mode was higher than that of the Harmonic mode. Besides, the Time and Space modes also influenced the temporal resolution, i.e. the temporal resolution of the Time mode was higher than that of the Space mode. Consequently, the 3DE datasets acquired by the S1H (Space 1 Harmonic) mode were of the lowest volume rate (14 ± 2 vps). Data acquisition was triggered by the R wave of the electrocardiogram and the Siemens automated contouring algorithm defined end diastole as the first (or occasionally the second) frame. Therefore, the EDV measure was independent of the volume rate. The ESV, however, was chosen from the smallest volume during the cardiac cycle. Since the normal time duration of the isovolumic relaxation period is 70 ± 12 ms (and will usually be even longer in pathological hearts) even the lowest volume rate in this study, i.e. the S1H mode, may be expected to be sufficient in capturing the smallest volume in the cardiac cycle.

The spatial resolution of the different imaging modes

By definition, the spatial resolution is inversely correlated to the temporal resolution (volume rate) because more time available per volume allows more ultrasound scan lines per volume. Therefore, spatial resolution was better in Harmonic and Space modes and best in the S1H (Space 1 Harmonic) mode.

The accuracy of the different imaging modes

There were significant differences in the LV volume and EF measurements between the six different imaging modes. Differences in the LV volume measures resulted from two main reasons: the general automated LV contour

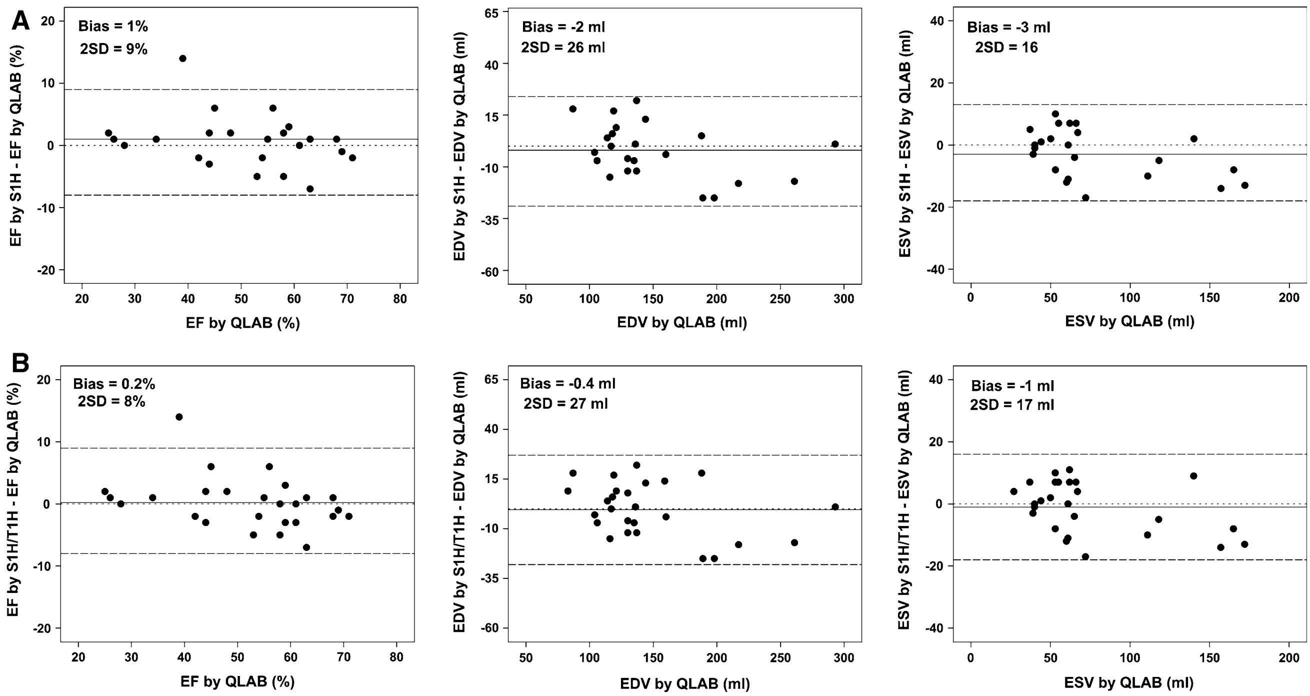

Fig. 3 Bland–Altman analysis comparing the ejection fraction and left ventricular volumes by **a** the Space 1 Harmonic mode with correct automated left ventricular contour tracking (n = 23); **b** the Space 1 Harmonic mode or Time 1 Harmonic mode (if the LV cavity did not fit completely in the acquisition sector of the Space 1 Harmonic mode) with correct automated left ventricular contour tracking (n = 28). Abbreviations as in Table 1

tracking and the near-field artifact. The automated LV contour was more toward the epicardium in the datasets acquired by the Fundamental modes, while more toward the LV cavity (particularly in the apex) in those acquired by the Harmonic modes. This might explain why the LV volumes of the Fundamental modes were larger than those of the Harmonic modes and the biases of the LV volumes compared with the 3DE QLAB measurements were positive in all Fundamental modes. The near-field artifact was very common, particularly in the T2H and T1H modes. In the datasets of the Fundamental modes, the near-field artifact was less common and the automated contour was more likely to cross over the near-field artefact and to track the stationary epicardium. Whereas in the datasets of the Harmonic modes, the apical contour was tracked better but seemed too much into the LV cavity (Fig. 4). In fact, the LV apical endocardium contour should be more outward toward the compacted myocardium [13–15]. However, since the apical segment is only one out of the total number of 17 LV segments and has a relatively limited volume capacity, the variances of the global LV volumes may only to a limited extend be caused by the variances in the apical volume alone. As shown in the overall patient population and 10 patients with correct LV contour tracking in all six imaging modes, the limits of agreement of LV volumes were, in contrast to the biases, quite comparable among the imaging modes.

In the previous studies it was reported that the Siemens RT-3DE automated contouring algorithm was accurate compared with CMR measurements [11, 12]. However, these studies did not specify which imaging modes were used. In the study of Chang et al. a volume rate of 13 ± 1 vps was reported [11], so most likely this study was performed using the S1H mode. In the study of Thavendiranathan et al. a volume rate of 32 ± 20 vps was reported [12]. It is hard to establish what imaging mode they used, but it could not be the S1H mode because to achieve such a high volume rate in this mode it would require to decrease the maximal size of the S1H acquisition sector, which is impossible to include the complete LV cavity. As discussed above, the different imaging modes led to substantial differences in the temporal and spatial resolutions of datasets acquired and in the LV volume and EF estimates. Therefore, it is important to outline this issue in a scientific article.

Practical use of the different imaging modes

For the use of the Siemens system in the real-world, the S1H mode was chosen as the primary imaging mode because of the favourable bias, correlation and limits of agreement compared with the 3DE QLAB measurements, as shown in the overall patient population and in the 10 patients with correct automated LV contour in all six

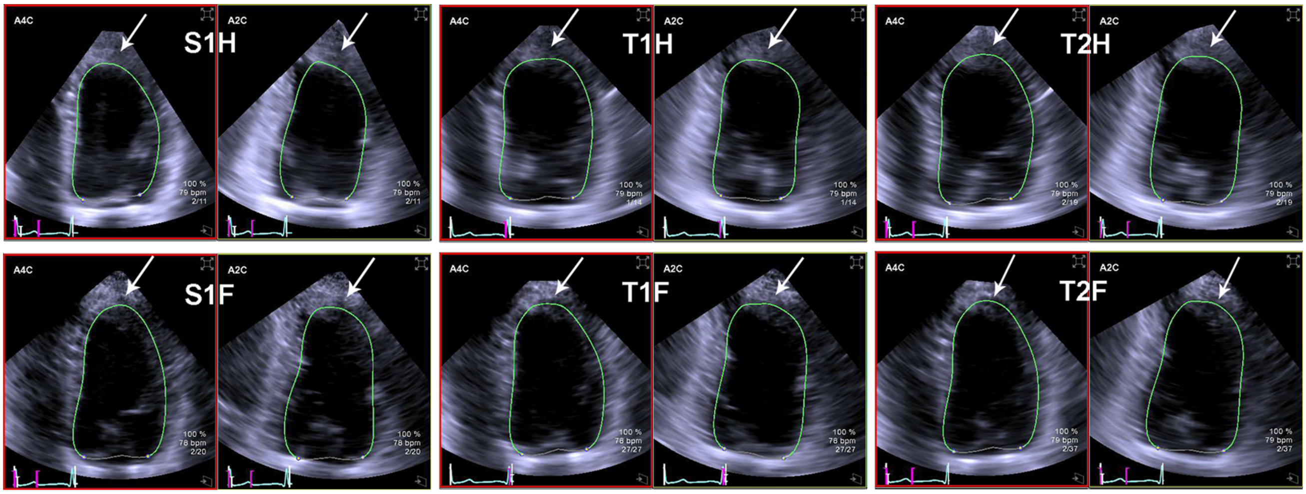

Fig. 4 The near-field artefact (*white arrows*) and automated left ventricular contour in the multiplanar reconstruction views of the 3D datasets acquired by the six imaging modes. *A4C* apical 4 chamber view, *A2C* apical 2 chamber view; other abbreviations as in Fig. 2

imaging modes. For similar reasons, the T1H mode was chosen as the best alternative if the LV cavity did not fit completely in the widest possible acquisition sector of the S1H mode. Using this approach, 28 patients out of 41 (68 %) could be analysed automatically and satisfyingly (with the intraobserver and interobserver variabilities of 0 % for analyzing the images acquired) with the automated algorithm; the S1H mode was used in 23 patients and the T1H mode in 5 patients. Compared with the 3DE QLAB measurements, the EF and LV volume estimates in these 28 patients were very accurate in terms of high correlation coefficient, small biases and tight limits of agreement. It should, however, also be recognized that due to false triggering of data acquisition and inferior echo quality, seven patients were not included in the data analysis of this study. Therefore, the true overall feasibility in the real-world of the Siemens RT-3DE automated algorithm was 28 of 48 patients (58 %). Importantly, this study was performed in a research environment and the sonographer was highly experienced with more than 25 years in echocardiography. In the real world, the outcomes may actually be less favourable and should be investigated in a real-world clinical study.

In a previous study from our group, we have demonstrated that 3DE QLAB datasets acquired and analyzed by the same investigator who did the 3DE QLAB analysis in the present study led to a minimal underestimation of the LV volumes (-7 ± 20 ml for EDV and -4 ± 8 ml for ESV) and EF (0 ± 6 %), compared with the CMR [8]. Since the biases of the LV volumes between Siemens RT-3DE and 3DE QLAB in the 28 patients were <1 ml, the extent of underestimation of LV volumes by the Siemens RT-3DE automated algorithm may be expected to be of the similar magnitude.

Limitations

One limitation could be the use of the manually corrected 3DE QLAB analysis as a gold standard for LV volumes and EF rather than CMR. As stated before, in a previous study from our group we have shown that 3DE QLAB measurements analyzed by the same investigator showed that the underestimation of LV volumes (-7 ± 20 ml for EDV and -4 ± 8 ml for ESV) and EF (0 ± 6 %) was extremely small, compared with CMR [8]. However, it should be recognized that in the literature in general 3DE underestimated the LV volumes compared with CMR. From this respect, it cannot be excluded that the positive volume bias seen in Fundamental mode may be to some extent false positive. Nevertheless, the bias in EF will still remain inferior to that seen in the Harmonic modes.

In particular in the T1F and T2F modes the LV endocardial border was more difficult to see in the MPR views of the 3D datasets and therefore the visual assessment of correct contour tracking by the Siemens automated algorithm may have been biased by the imaging modes.

Finally, patients with abnormal LV shapes as seen in severely dilated and hypertrophic cardiomyopathy were not included in this study and the influence of the imaging modes on the EF and LV volume estimates in these patients is therefore not known.

Conclusions

The accuracy of the Siemens automated RT-3DE algorithm in measuring the LV volumes and EF is significantly influenced by the different imaging modes, caused by differences in temporal and spatial resolutions. The S1H mode may be the preferred 3D acquisition mode, supplemented by the T1H acquisition mode in enlarged LVs which cannot be included completely in the acquisition sector of the S1H mode. By this method the majority of patients can be analyzed automatically with excellent results.

Conflict of interest None.

References

1. Wang TJ, Evans JC, Benjamin EJ, Levy D, LeRoy EC, Vasan RS (2003) Natural history of asymptomatic left ventricular systolic dysfunction in the community. Circulation 108(8):977–982. doi:10.1161/01.CIR.0000085166.44904.7901.CIR.0000085166.44904.79
2. White HD, Norris RM, Brown MA, Brandt PW, Whitlock RM, Wild CJ (1987) Left ventricular end-systolic volume as the major determinant of survival after recovery from myocardial infarction. Circulation 76(1):44–51
3. Jenkins C, Bricknell K, Hanekom L, Marwick TH (2004) Reproducibility and accuracy of echocardiographic measurements of left ventricular parameters using real-time three-dimensional echocardiography. J Am Coll Cardiol 44(4):878–886. doi:10.1016/j.jacc.2004.05.050S0735-1097(04)01117-9
4. Kuhl HP, Schreckenberg M, Rulands D, Katoh M, Schafer W, Schummers G, Bucker A, Hanrath P, Franke A (2004) High-resolution transthoracic real-time three-dimensional echocardiography: quantitation of cardiac volumes and function using semi-automatic border detection and comparison with cardiac magnetic resonance imaging. J Am Coll Cardiol 43(11):2083–2090. doi:10.1016/j.jacc.2004.01.037S073510970400484X
5. Soliman OI, Krenning BJ, Geleijnse ML, Nemes A, Bosch JG, van Geuns RJ, Kirschbaum SW, Anwar AM, Galema TW, Vletter WB, ten Cate FJ (2007) Quantification of left ventricular volumes and function in patients with cardiomyopathies by real-time three-dimensional echocardiography: a head-to-head comparison between two different semiautomated endocardial border detection algorithms. J Am Soc Echocardiogr 20(9):1042–1049. doi:10.1016/j.echo.2007.02.011
6. Soliman OI, Krenning BJ, Geleijnse ML, Nemes A, van Geuns RJ, Baks T, Anwar AM, Galema TW, Vletter WB, ten Cate FJ (2007) A comparison between QLAB and TomTec full volume reconstruction for real time three-dimensional echocardiographic quantification of left ventricular volumes. Echocardiography 24(9):967–974. doi:10.1111/j.1540-8175.2007.00502.x
7. Mor-Avi V, Jenkins C, Kuhl HP, Nesser HJ, Marwick T, Franke A, Ebner C, Freed BH, Steringer-Mascherbauer R, Pollard H, Weinert L, Niel J, Sugeng L, Lang RM (2008) Real-time 3-dimensional echocardiographic quantification of left ventricular volumes: multicenter study for validation with magnetic resonance imaging and investigation of sources of error. JACC Cardiovasc Imaging 1(4):413–423. doi:10.1016/j.jcmg.2008.02.009
8. Soliman OI, Kirschbaum SW, van Dalen BM, van der Zwaan HB, Mahdavian Delavary B, Vletter WB, van Geuns RJ, Ten Cate FJ, Geleijnse ML (2008) Accuracy and reproducibility of quantitation of left ventricular function by real-time three-dimensional echocardiography versus cardiac magnetic resonance. Am J Cardiol 102(6):778–783. doi:10.1016/j.amjcard.2008.04.062
9. Dorosz JL, Lezotte DC, Weitzenkamp DA, Allen LA, Salcedo EE (2012) Performance of 3-dimensional echocardiography in measuring left ventricular volumes and ejection fraction: a systematic review and meta-analysis. J Am Coll Cardiol 59(20):1799–1808. doi:10.1016/j.jacc.2012.01.037
10. Muraru D, Badano LP, Piccoli G, Gianfagna P, Del Mestre L, Ermacora D, Proclemer A (2010) Validation of a novel automated border-detection algorithm for rapid and accurate quantitation of left ventricular volumes based on three-dimensional echocardiography. Eur J Echocardiogr 11(4):359–368. doi:10.1093/ejechocard/jep217
11. Chang SA, Lee SC, Kim EY, Hahm SH, Jang SY, Park SJ, Choi JO, Park SW, Choe YH, Oh JK (2011) Feasibility of single-beat full-volume capture real-time three-dimensional echocardiography and auto-contouring algorithm for quantification of left ventricular volume: validation with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 24(8):853–859. doi:10.1016/j.echo.2011.04.015
12. Thavendiranathan P, Liu S, Verhaert D, Calleja A, Nitinunu A, Van Houten T, De Michelis N, Simonetti O, Rajagopalan S, Ryan T, Vannan MA (2012) Feasibility, accuracy, and reproducibility of real-time full-volume 3D transthoracic echocardiography to measure LV volumes and systolic function: a fully automated endocardial contouring algorithm in sinus rhythm and atrial fibrillation. JACC Cardiovasc Imaging 5(3):239–251. doi:10.1016/j.jcmg.2011.12.012
13. Krenning BJ, Kirschbaum SW, Soliman OI, Nemes A, van Geuns RJ, Vletter WB, Veltman CE, Ten Cate FJ, Roelandt JR, Geleijnse ML (2007) Comparison of contrast agent-enhanced versus non-contrast agent-enhanced real-time three-dimensional echocardiography for analysis of left ventricular systolic function. Am J Cardiol 100(9):1485–1489. doi:10.1016/j.amjcard.2007.06.042
14. Malm S, Frigstad S, Sagberg E, Larsson H, Skjaerpe T (2004) Accurate and reproducible measurement of left ventricular volume and ejection fraction by contrast echocardiography: a comparison with magnetic resonance imaging. J Am Coll Cardiol 44(5):1030–1035. doi:10.1016/j.jacc.2004.05.068S0735-1097(04)01217-3
15. Thomson HL, Basmadjian AJ, Rainbird AJ, Razavi M, Avierinos JF, Pellikka PA, Bailey KR, Breen JF, Enriquez-Sarano M (2001) Contrast echocardiography improves the accuracy and reproducibility of left ventricular remodelling measurements: a prospective, randomly assigned, blinded study. J Am Coll Cardiol 38(3):867–875