European Heart Journal – Cardiovascular Imaging (2013) **14**, 285–293
doi:10.1093/ehjci/jes184

Use of three-dimensional speckle tracking to assess left ventricular myocardial mechanics: inter-vendor consistency and reproducibility of strain measurements

Luigi P. Badano*, Umberto Cucchini, Denisa Muraru, Osama Al Nono, Cristiano Sarais, and Sabino Iliceto

Department of Cardiac, Vascular and Thoracic Sciences, University of Padua, Via Giustiniani 2, 35128 Padua, Italy

Received 23 June 2012; revised 9 August 2012; accepted after revision 11 August 2012; online publish-ahead-of-print 11 September 2012

Aims Since there is insufficient data available about the inter-vendor consistency of three-dimensional (3D) speckle-tracking (STE) measurements, we undertook this study to (i) assess the inter-vendor consistency of 3D LV global strain values obtained using two different scanners; (ii) identify the sources of inter-vendor inconsistencies, if any; and (iii) compare their respective intrinsic variability.

Methods and results Sixty patients (38 ± 12 years, 64% males) with a wide range of LV end-diastolic volumes (from 74 to 205 ml) and ejection fractions (from 17 to 70%) underwent two 3D LV data set acquisitions using VividE9 and Artida ultrasound systems. Global longitudinal (Lε), radial (Rε), circumferential (Cε) and area (Aε) strain values were obtained offline using the corresponding 3D STE softwares. Despite being significantly different, Lε showed the closest values between the two platforms (bias = 1.5%, limits of agreement (LOA) from −2.9 to −5.9%, $P < 0.05$). Artida produced significantly higher values of both Cε and Aε than VividE9 (bias = 6.6, LOA: −14.1 to 0.9%, and bias = 6.0, LOA = −28.2–8.6%, respectively, $P < 0.001$). Conversely, Rε values obtained with Artida were significantly lower than those measured using VividE9 platform (bias = −24.2, LOA: 1.5–49.9, $P < 0.001$). All strain components showed good reproducibility (intra-class correlation coefficients: 0.82–0.98), except for Rε by Artida, which showed only a moderate reproducibility.

Conclusion Apart from Lε, the inter-vendor agreement of Rε, Cε and Aε measured with Artida and VividE9 was poor. Reference values should be specific for each system and baseline and follow-up data in longitudinal studies should be obtained using the same 3D STE platform.

Keywords Three-dimensional echocardiography • Strain • Left ventricular function • Myocardial mechanics • Myocardial deformation • Speckle tracking • Reproducibility • Deformation imaging

Introduction

The development of myocardial deformation analysis by echocardiography has allowed the quantitation of the myocardial function at regional and global levels, aiming to render its assessment more objective, accurate and reproducible.[1] Tissue velocity imaging has been the first technique used to calculate myocardial deformation and remains the most extensively evaluated technology for this purpose.[1] However, the accurate measurement of myocardial deformation using Doppler is critically dependent on the angle of insonation; therefore limited to the assessment of its longitudinal component. Two-dimensional strain is a technique of quantifying myocardial deformation from continuous frame-by-frame tracking of acoustic speckles, which is angle independent (provides measurements of three deformation components: longitudinal, radial and circumferential), less subject to artefacts, and simpler to

* Corresponding author. Tel: +39 (0) 49 8218640; fax: +39 (0) 49 8211802, Email: lpbadano@gmail.com

obtain than Doppler-derived tissue velocity imaging.[1] However, cardiac motion is a complex combination of apex-to-base lengthening and shortening with simultaneous twisting and therefore speckle tracking methods based on two-dimensional imaging are limited by the significant speckle decorrelation when out-of-plane motion occurs. Therefore, the accurate evaluation of myocardial strain in the left ventricular (LV) myocardial segments requires an advanced technology that uses a three-dimensional (3D) tracking system. The newly developed 3D speckle-tracking echocardiography (3D STE) based on 3D data sets has the potential to circumvent the limitations of two-dimensional STE in the assessment of LV myocardial deformation.

Although several clinical applications of 3D STE have been reported to assess the regional[2–4] and global[5–10] LV function, to quantify the LV dyssynchrony[11–14] and to evaluate the LV myocardial function in hypertensive disease,[15] data about reproducibility of the technique are scarce and restricted to a single echo machine.[3,16] There is a single paper reporting the inter-vendor consistency of 3D STE measurements, but only in normal subjects and involving only one of the commercially available echo platforms which provide the 3D STE package on board.[17] Knowledge of these data about commercially available echo platforms in patients examined in routine clinical practice is pivotal for this technique to be implemented in both clinical and research arenas.

Accordingly, in the present study we used the two commercially available platforms equipped with 3D STE technique to obtain, in the same patient, two 3D STE measurements of LV deformation parameters in order to (i) assess their inter-vendor consistency; (ii) investigate their intrinsic variability by assessing their inter- and intra-observer, as well as test/re-test reproducibility; and (iii) identify some of the sources of inter-vendor inconsistencies, if any.

Methods

Study population

Seventy-one consecutive patients, referred as in- or outpatients to our echo-lab for a clinically indicated routine echocardiography, were enrolled in the study.

The unique inclusion criteria were the presence of sinus rhythm and ability to breathhold for 5–10 s during the examination. Eleven patients (15%) were excluded due to poor 2D image quality (more than two LV segments not adequately visualized without contrast infusion) or persistent stitching artefacts at several 3D data set acquisitions. Accordingly, the patient study group consisted of 60 patients (*Table 1*).

Table 1 Demographic and clinical characteristics of the study patients

Variables	*n* = 60 patients
Males (%)	41 (68%)
Age (years)	58 ± 15 (range: 30–87)
Body surface area (m^2)	1.85 ± 0.18
Heart rate (bpm)	64 ± 12
Systolic blood pressure (mmHg)	120 ± 18
Diastolic blood pressure (mmHg)	74 ± 11
Clinical indications for echo study	
Ischemic heart disease	32 (53%)
Valvular heart disease	9 (15%)
Normal	5 (8%)
Cardiomyopathies	4 (7%)
Arterial hypertension	2 (3%)
Congenital heart disease	2 (3%)
Other	6 (10%)

Echocardiography

All examinations were performed with commercially available echocardiographic systems (Vivid E9, GE-Healthcare, Horten, Norway, and Artida, Toshiba Medical Systems Corporation, Tokyo, Japan) equipped with the 4V and the PST-25SX phased-array matrix transducers, respectively. Two 3DE LV data sets were acquired by the same experienced examiner at the beginning and at the end of the standard echocardiographic examination using both echo platforms in sequence and without changing the patient position. Consecutive four-beat ECG-gated subvolumes were acquired from the apical approach using second-harmonic imaging, during an end-expiratory apnoea to generate the full-volume data set using the wide-angle default settings of each scanner recommended by the two manufacturers.[15,18] Care was taken to encompass the entire LV cavity within the data set. The quality of the acquisitions was then verified in each patient by selecting the multislice display mode available on the machines to ensure optimal imaging of the entire LV wall at each short-axis level and, if unsatisfactory, the data set were re-acquired. Data sets were digitally stored in a raw-data format and exported to separate workstations equipped with the two commercially available softwares (EchoPAC v110.1.3, GE Healthcare, Horten, Norway, and 3D WMT, Toshiba Medical Systems Corporation, Tokyo, Japan) for offline analysis of STE LV myocardial deformation measurements, together with LV volumes, mass and ejection fraction quantitation.

3D-strain measurements

A single experienced investigator analysed the data sets in random order, unaware of the identity of the patients.

Data sets acquired with Artida were displayed in a 5 slice mode (*Figure 1 A*). The LV was automatically divided into 17 3D segments using standard segmentation.[19] The following parameters of global myocardial deformation (Lagrangian strain) were measured: longitudinal (Lε), circumferential (Cε), radial (Rε) and area (Aε) strain. Measurements were performed using a methodology extensively described by Seo *et al.*[2] and time–strain curves were displayed with drift compensation of any segmental trace and temporal strain–volume variations presented in a wide variety of colour-coded displays (*Figure 1 A*).

Data sets acquired with Vivid E9 were analysed using the 4D-AutoLVQ package (EchoPAC v110.1.3, GE-Healthcare, Horten, Norway). The end-diastolic frames needed for contour detection were automatically displayed in a quad view (*Figure 1 B*). Manual alignment by pivoting and translating the four-chamber plane was performed to align the three apical views in order that the corresponding intersection line of all planes was placed in the middle of the LV cavity, crossing the LV apex and the centre of mitral valve in each view. We used the semi-automated option to subsequently identify a fitting geometric model. The software required the manual input of only two single points (one point at the apex and another one at the tip of the mitral leaflet) on the end-diastolic and end-systolic frames of the four-chamber view slice. The software automatically detected LV

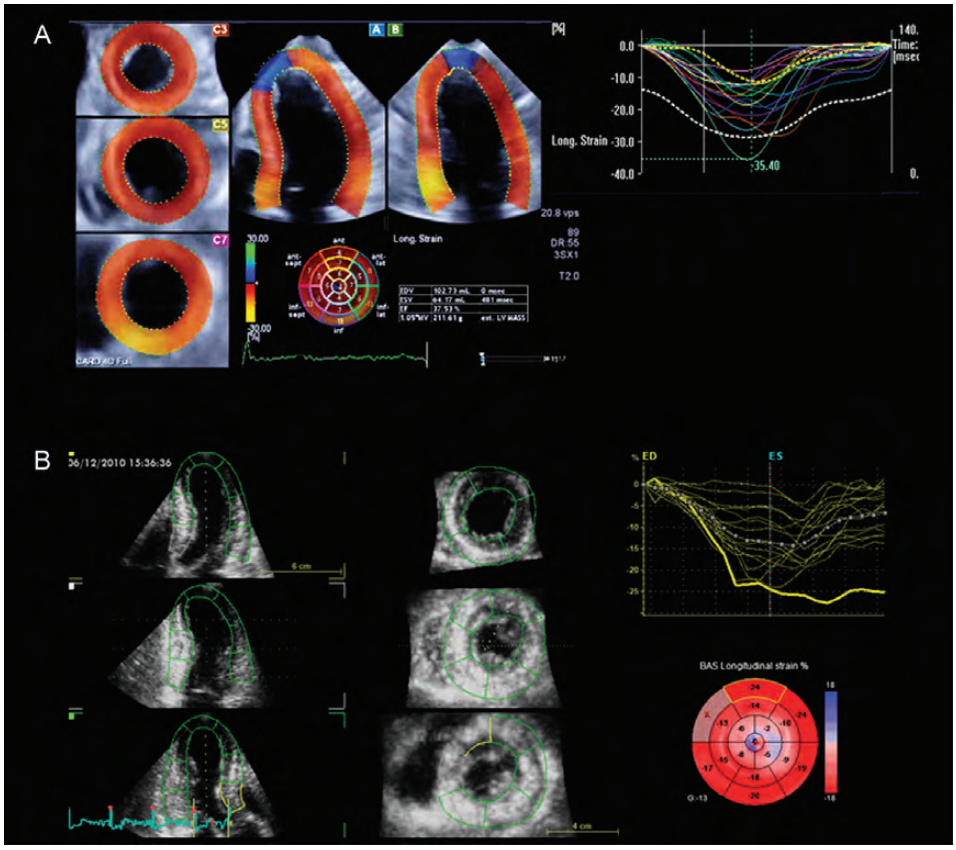

Figure 1 Left ventricular data set display with 3D speckle-tracking analysis of myocardial deformation using Artida (*A*) and Vivid E9 (*B*) platforms. On the right side of each panel, the derived time–strain curves are shown. Time–strain curves obtained with Artida show a drift compensation (i.e. all curves are forced to reach the zero baseline at end diastole: upper right panel). This does not apply to the time–strain curves provided by Vivid E9 (lower right panel), a large drift (>12%) leading to automated segment rejection by this software; a time–strain curve with a significant drift is highlighted in yellow.

cavity endocardial border in 3D and provided the measured LV volumes. If endocardial border detection was judged unsatisfactory by the examiner, LV endocardial borders could be manually adjusted in a multiplanar layout (three apical and three transverse planes) by a point-click method, with secondary immediate automated refinement of boundary detection accordingly.[20]

After LV volumes and ejection fraction measurements, an automatic trace of the epicardial border was displayed to identify the region of interest required for LV mass and myocardial deformation measurements by 3D STE. Epicardial trace could be manually adjusted with the same point-click method. The deformation parameters were reported as global (both peak and end-systolic) and regional (end-systolic) Lε, Cε, Rε and Aε, and presented as color-coded polar maps and time–strain traces of an LV 17-segment model. As opposed to the 3D WMT software, the 4DAutoLVQ package does not apply any drift compensation to strain curves, and LV segments showing a significant drift of Lε (more than 12 percentage points) of end-systolic strain curves from the baseline were rejected from the subsequent analysis (*Figure 1 B*). Global strain was not computed when more than three LV segments were rejected and these patients were excluded from the final analysis.

The mean time spent for the analysis with each software was recorded for subsequent comparison.

The inter-vendor consistency of 3D strain measurements was assessed by comparing the measurements of each strain component obtained with these two products.

Reproducibility of 3D strain measurements

To explore the impact of the intrinsic variability of repeated measurements on inter-vendor strain differences, we assessed the intra-, inter-observer and test/re-test reproducibility on 20 randomly selected LV data sets. To test the intra-observer variability, a single observer analysed the same data sets on two different occasions separated by 1-week interval. To test the inter-observer variability, a second observer analysed the data without knowledge of the first observer's measurements. Test/re-test variability was assessed by comparing the measurements obtained by the same observer from the data set acquired at the beginning of the routine echo study and from the second one acquired at the end of the echo study (around 40 min later) using the same platform.

Analysis of sources of inter-vendor inconsistency

In order to explore the reasons for the observed differences between the two vendors, we analysed the influence of the specific software

used, image quality, and temporal resolution of 3D data sets on 3D strain measurements.

The influence of the softwares used to analyse the 3D data sets was assessed by comparing 3D strain results obtained by a single observer who analysed all 3D data sets acquired with both platforms with a vendor-independent software (4D LV Analysis, TomTec Imaging Systems, Unterschleissheim, Germany). Image quality of 3D data sets was independently scored by two observers by looking at sliced images and was graded as poor (incomplete endocardial border visualization), fair (complete, but suboptimal visualization of endocardial border) and good (clear visualization of the whole edocardial border). In the case of disagreement between the two observers, a consensus was reached by joint review. 3D strain measurements obtained from data sets scored as having good quality with both platforms were compared. In addition, the number of LV segments which did not enter within the image sector of the sliced data sets was collected.

To test the influence of data set temporal resolution on the inter-vendor consistency of 3D strain measurement, in 15 patients an additional data set was acquired with Artida at 30 vps immediately after the reference one in order to reach the same temporal resolution of data sets acquired with Vivid E9.

The study protocol was approved by our Institutional Ethics Committee and all patients gave informed consent consistent with this protocol.

Statistical analysis

Data are summarized as the mean ± SD, frequencies and ranges, as appropriate. Continuous data were compared with the two-tailed Student's *t*-test for paired and unpaired data, respectively. For each deformation parameter, the consistency between each pair of measurements obtained with the two platforms was assessed using Bland–Altman statistics to calculate the systematic bias and limits of agreement (LOA) and with Pearson's correlation coefficients. Intra- and inter-observer, as well as the test/re-test variability were assessed using Bland–Altman statistics (coefficient of repeatability, CR) and intra-class correlation (intra-class correlation coefficient, ICC). Comparison of Pearson's correlation coefficients was performed using the Z score statistic. A probability value of <0.05 was considered statistically significant. Data analysis was performed using SPSS version 15.0 (SPSS, Inc., Chicago, IL, USA) and MedCalc for Windows, 11.4.3.0 release (Mariakerke, Belgium) statistical softwares.

Results

Feasibility of 3D LV data set acquisition was 85% (60 out of 71 attempted) and the final study group comprised 60 patients with a wide range of age and body surface areas (*Table 1*), LV volumes and ejection fractions (*Table 2*). An average heart rate was similar between data sets acquired with Artida and Vivid E9 (*Table 2*). Conversely, the data set volume size was significantly lower and temporal resolution was significantly higher for those acquired with Vivid E9 (*Table 2*). The quality of sliced images obtained from the 3D data sets was significantly better with Vivid E9 (*Table 2*). However, the larger volume size obtained by Artida allowed to achieve a more complete visualization of LV segments using multislice display: incomplete visualization (i.e. 1–3 missing apical segments) was 28% with Vivid E9 and 2% with Artida ($P < 0.0001$).

All segments from all available data sets (100%) were analysed with the 3D WMT software. Conversely, two patients with more than three LV segments rejected by automatic tracking using 4DAutoLVQ software by EchoPac were excluded because inadequate for global strain determination. Sixty-four LV segments (6.3%) from the remaining 58 patients were rejected because of significant drift of the strain traces. Inadequately tracked segments were more likely located at the basal level of the LV with a gradient towards mid-ventricle and apical regions (*Figure 2*).

The entire time required to analyse the 3D data sets and obtain the final results was not statistically different between the two platforms (3 min 58 s ± 36 s and 3 min 44 s ± 29 s for Artida and Vivid E9, respectively; P = NS).

Comparison of LV myocardial strain values between Artida and Vivid E9

For each vendor, there was no significant difference between the global peak strain values and global strain measured at end systole (*Table 3*). Artida platform produced significantly higher absolute values of both Cε and Aε than Vivid E9 (*Table 3*). Lε and Rε obtained with Artida were significantly lower than those measured using Vivid E9 platform (*Table 3*, *Figure 3*). Among the various strain measurements, Lε showed the smallest bias and the narrowest LOA between the two platforms. Conversely, Rε showed the largest bias and the widest limits of LOA between vendors, as well as the poorest correlation among all strain components (*Table 3*, Figure 4).

Reproducibility

Reproducibility of the strain measurements obtained with the two ultrasound systems are summarized in *Table 4*. Lε and Cε were found to be comparably and highly reproducible with both vendors (*Table 4*). Among all strain components, Rε was the least reproducible parameter with both systems. Overall, the reproducibility of the different strain components was significantly better with Vivid E9 than with Artida (*Table 4*).

Impact of image quality and temporal resolution

Data sets obtained from 22 patients were graded as 'good quality' with both software packages and underwent a subset analysis to assess the inter-vendor consistency of 3D strain measurements (*Table 5*). Selecting only the data sets with good image quality for analysis showed a trend towards an improved inter-vendor correlation of strain measurements, but it did not change the main results of the analysis performed on the whole study population. Apart Lε, all strain components differed significantly between the two ultrasound systems and the extent of biases and LOA were comparable between the subset of patients with good image quality and the whole study population.

To assess the impact of temporal resolution on 3D STE deformation measurements, we compared 3D strain measurements obtained from Artida data sets acquired at 20 vps (default settings) and at 30 vps (a volume rate similar to the one reached with Vivid E9). All four strain components showed no significant difference in their values between data sets acquired at 20 vps and those acquired at 30 vps (*Table 6*).

When a vendor-independent software was used to assess Lε in order to eliminate the potential variability due to vendor-specific

Table 2 Echocardiographic characteristics of study patients

Echocardiographic variables	Artida	Vivid E9	*P* value
Data set size (degrees)	90° × 90° (default)	60° × 60° (large)	
Data set volume rate (vps)	21 ± 1	30 ± 3	<0.001
Heart rate (bpm)	65 ± 14	65 ± 13	NS
Image quality			0.01
Good, *n* (%)	30 (50)	38 (64)	
Fair, *n* (%)	17 (29)	20 (33)	
Poor, *n* (%)	13 (21)	6 (3)	
Rejected segments (%)	0 (0)	64 (6.3)	<0.0001
End-diastolic volume (ml)	121 ± 31 (range: 52–197)	127 ± 35 (range: 74–205)	NS
End-systolic volume (ml)	63 ± 30 (range: 22–161)	63 ± 32 (range: 22–165)	NS
Ejection fraction (%)	50 ± 13 (range: 17–65)	53 ± 13 (range: 19–70)	NS

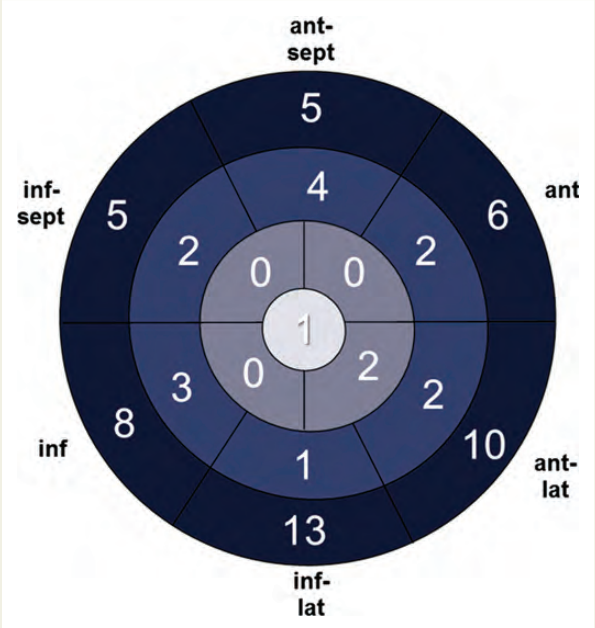

Figure 2 Bull's eye display showing the location of the left ventricular rejected segments by the EchoPAC software. A significantly larger number of patients had inadequately tracked segments at the basal left ventricular region, with a basal-apical gradient (numbers represent patients).

analysis softwares, we found a significant difference between Lε values obtained examining the data set acquired using Artida and Vivid E9 (−14.3 ± 5.3 and −12.9 ± 4.3%, respectively, $P = 0.0001$, bias = −1.4, LOA = 4.9 ± 0.1%).

Discussion

The main results of our study can be summarized as follows: (i) the inter-vendor agreement of Rε, Cε and Aε measured with Artida and Vivid E9 was poor; (ii) only Lε was comparable between the two vendors and also with values obtained with TomTec® software; (iii) the intrinsic variability of the different strain components obtained with the two systems tested was relatively low (except for Rε), but varied significantly among strain parameters and between the two vendors; (iv) increasing data set temporal resolution from 20 to 30 vps and image quality do not seem to impact significantly on the inter-vendor agreement of strain measurements; and (v) the use of a vendor-independent analysis software did not eliminate the differences in the Lε measurement.

The development of the 3D STE technique allows one to detect in a fast and comprehensive manner all the components (vectorial and rotational) of the myocardial deformation, without the intrinsic limitations of previous technologies based on tissue velocity imaging or two-dimensional STE.[3,16,21] However, since an accurate and reproducible assessment of the LV myocardial function is pivotal for both clinical and research purposes, 3D used for quantitation of myocardial deformation should be evaluated as rigorously as any therapeutic intervention before starting its systematic application in everyday clinical practice.[22] For these reasons, along with the accuracy that should be determined by comparing the measurements with those performed with a reference technique, reproducibility (represented by the reciprocal of the variability of measurements made by a single observer in different occasions—intra-observer variability or by different observers—inter-observer variability) and repeatability (the reciprocal of variability of measurements made on the same patients, in the same conditions in two different occasions—test/re-test variability or made using different systems and analysis softwares—inter-vendor variability) are crucial factors in determining the clinical relevance and reliability of any diagnostic technique.

To our knowledge, this is the first study comparing the inter-vendor consistency and the intrinsic variability of 3D strain measurements obtained with two commercially available echocardiographic platforms in patients with a wide range of LV size and function. Gayat *et al.*[17] compared strain values measured on data sets acquired from 30 subjects with the normal LV function using Artida and iE33 (Philips Healthcare, Andover, Massachusetts, USA) and analysed them using 3D WMT and 4D LV function software packages. They found that the inter-technique agreement was

Table 3 Results of global 3D strain measurements and comparison between Artida and Vivid E9 platforms

Global ε (%) (n = 58)	Artida	Vivid E9	Bias	LOA	ICC
Longitudinal					
End systolic	13.5 ± 4.5	−14.6 ± 4.7**	1.1	6.4 to −4.2	0.830
Peak	−14.1 ± 4.2	−15.2 ± 4.8**	1.1	6.4 to −4.2	0.820
Circumferential					
End systolic	22.7 ± 8.3	−14.9 ± 4.6*	7.8	2.7 to −18.3	0.683
Peak	22.8 ± 8.3	−15.8 ± 4.9*	7.0	2.5 to −16.4	0.750
Radial					
End systolic	16.4 ± 9.1	40.5 ± 14.4*	−24.1	0.2 to 48.4	0.522
Peak	7.9 ± 8.4	42.1 ± 15.1*	−24.2	1.5 to 49.9	0.504
Area strain					
End systolic	−33.7 ± 10.4	−26.4 ± 7.6*	−7.3	3.1 to −17.8	0.830
Peak	33.8 ± 10.4	−27.2 ± 7.9*	−6.6	3 .4 to −16.6	0.848

ε, strain; ICC, intra-class correlation; LOA, limits of agreement. Bias and LOA represent absolute (i.e. strain-percent) values.
*$P < 0.001$, **$P < 0.01$.

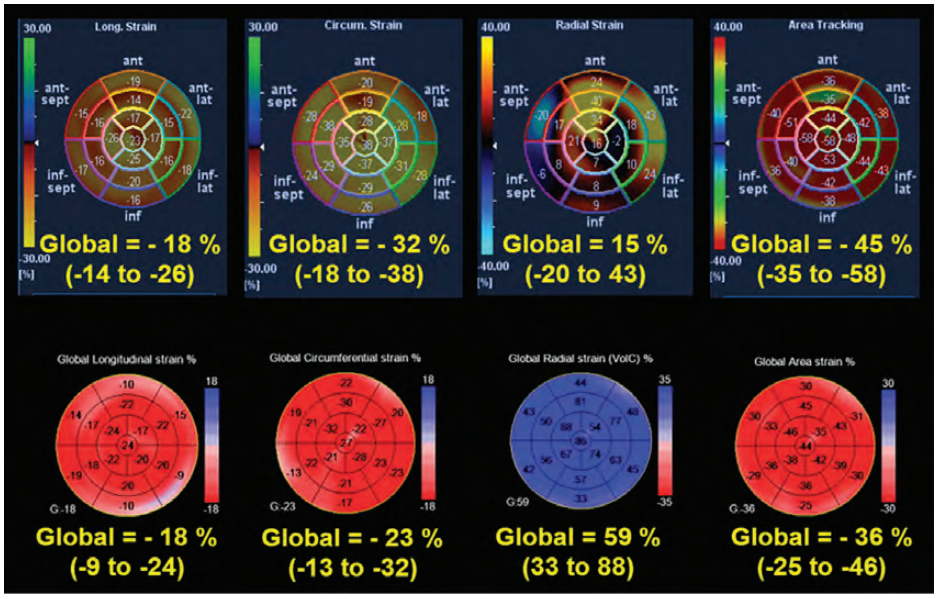

Figure 3 Comparison of longitudinal, circumferential, radial and area strain obtained from the same patient using Artida (upper panels) and Vivid E9 (lower panels). Only the global longitudinal component of the strain was comparable between the two platforms. However, looking at segmental values, also the longitudinal component of the strain showed significant differences between the two platforms. Notice that the bull's eyes in the lower panels are rotated clockwise by 60° and the segments at 12 o'clock represent the anterior septum.

poor (it improved when data sets acquired with different platforms were analysed using a vendor-independent software, i.e. the 4D LV function), and that the discordance level was beyond the intrinsic measurement variability of any of the tested combinations of software and hardware. However, they analysed only subjects with the normal LV function and measured only longitudinal and circumferential components of strain. Finally, they did not assess an important parameter to consider when a technique has to be used to follow patients, which is the test/re-test variability of measurements.

In our study population, 3D STE was reasonably feasible and measurements were reproducible (except for Rε, *Table 4*) with both echocardiographic platforms. However, our data show that, among the various strain components, only the Lε (despite being significantly different between the two systems) was at some extent comparable between Artida and Vivid E9. Cε and Aε showed the mean differences between the two platforms around 30 and 23%, respectively. Rε values obtained with Artida and Vivid E9 were so different (absolute values of 17 vs. 44%,

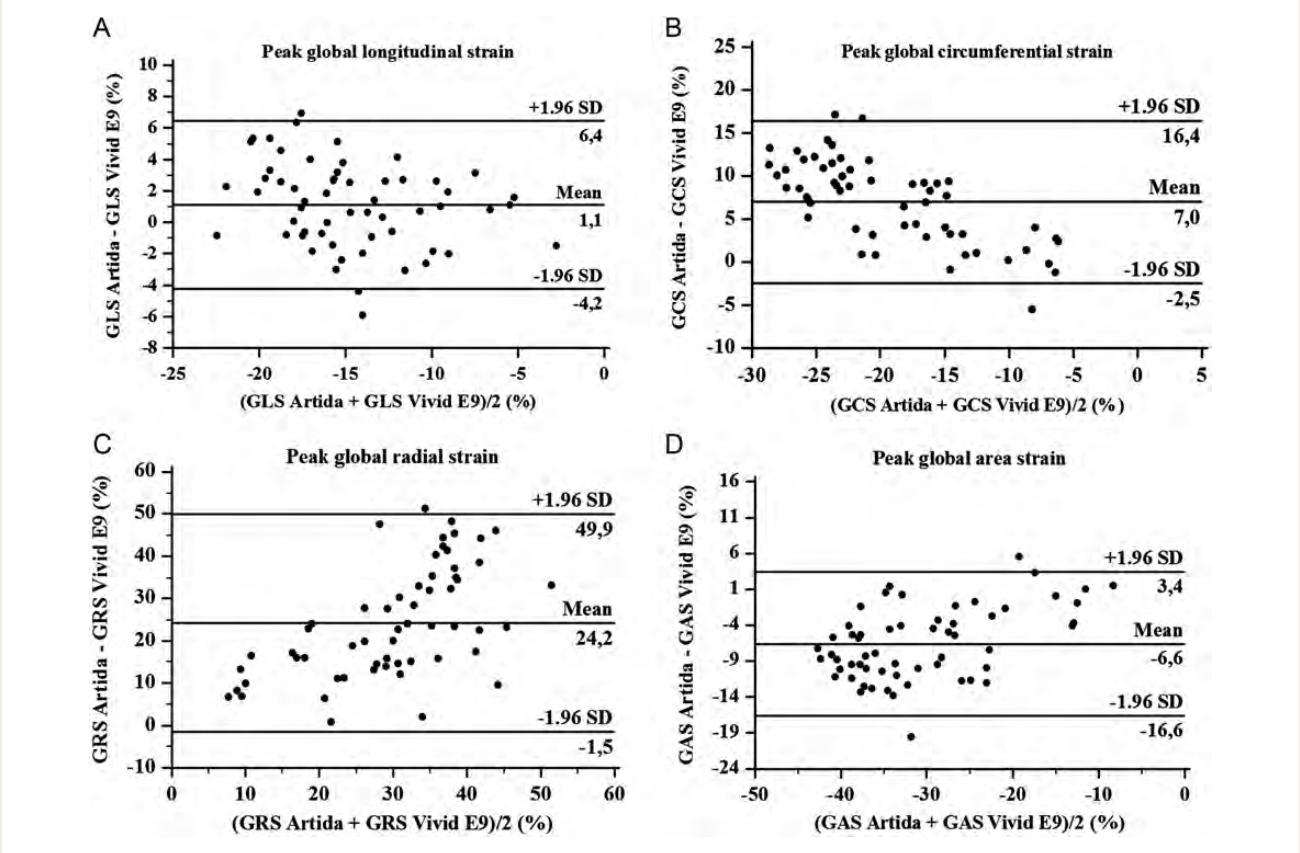

Figure 4 Bland–Altman plots representing the agreement between the peak strain components obtained from Artida and Vivid E9 platforms. Axis values are calculated as absolute values (i.e. not taking into account the negative or positive value of the corresponding strain parameter).

respectively), that it seems as if they were measured with different scales. However, Rε obtained with the two systems used in our study seems to measure different entities, since the ICC between Rε measured with Artida and Vivid E9 was only moderate. This is mainly due to the different ways used by the two platforms to compute Rε. Rε by 3D WMT is estimated by both endocardial and epicardial speckle tracking, so that Rε measurements are highly dependent on image quality compared with those of the Lε and Cε components, which are estimated only by endocardial speckle data.[4] This translates in a lower accuracy and reproducibility of Rε with this platform in comparison with Cε and Lε,[2,4] consistent with our data. Conversely, EchoPAC does not actually measure the Rε, but it estimates it from Aε, assuming that each LV segment maintains a constant volume throughout cardiac cycle. This explains the high reproducibility and repeatability of Rε calculations obtained with EchoPAC.

Noticeably, the inter-vendor biases for all strain measurements were significantly larger than the intrinsic technique variability of each ultrasound system, as detected by the reproducibility and repeatability analyses.

Trying to find out whether any technical reason could explain such different measurements, we found that neither temporal resolution (at least in the range of volume rates tested in our study, i.e. from 20 to 30 vps), nor image quality have a significant impact on the different measurements obtained from the two tested platforms. However, it should be acknowledged that data sets with poor image quality were excluded from our study and that, given the high intrinsic variability of 3D strain estimates, the impact of the remaining range of image quality could have been too small to be detected with the size of our study population. Moreover, Cε and Aε by Artida showed significantly higher amplitudes than those obtained by VividE9, while Rε by Artida was significantly lower than the one obtained by VividE9. Even if some differences can be explained by the fact that 3D WMT tracks mainly speckles located in the endocardial layer and global strains are calculated as mathematical averages of all segmental values, while EchoPAC tracks speckles across the whole wall thickness and global strains are calculated as weighted spatial averaging of segmental values, these seem to be only part of the problem.

On the other end, this is confirmed by the fact that Lε measurements provided by the two vendors are quite close. However, we have found that two data sets acquired in the same patients during the same echocardiographic study by Artida and Vivid E9 and analysed using a single vendor-independent software (i.e. 4D LV function) provide Lε measurements which are discordant beyond the intrinsic variability of the respective ultrasound systems. This is likely linked to the 3D data set characteristics, which differ from vendor to vendor. The ability of a given software package to accurately track wall motion may be affected by these 3D data set characteristics.

Study limitations

First, our study population was relatively limited. However, we enrolled a two-fold higher number of patients than in similar papers addressing the issue of the inter-vendor consistency of strain measurements,[17,23] and differently from the previous studies we included patients with an impaired LV function. Secondly, data set temporal resolution and volume size differed significantly between the tested ultrasound systems. However, we used standard machine settings on purpose in order to assess the inter-vendor agreement of measurements performed with the systems settings used in the clinical routine. Moreover, we have also shown that strain measurements obtained with Artida at standard settings were similar to those obtained at higher volume rates which were similar to those obtained with Vivid E9. Third, image quality was judged visually and not assessed on an objective scale. Thus, the scoring of the data sets in terms of image quality might have been inaccurate. However, we are not aware of any accepted objective grading system for the quality of 3D images.

Table 4 Intra-, inter-observer and test/re-test reproducibility of 3D strain measurements obtained with Artida and Vivid E9

n = 20 patients	Artida		Vivid E9	
	Bias ± CR	ICC	Bias ± CR	ICC
Intra-observer variability				
Peak Lε (%)	0.2 ± 3.4	0.95	0.5 ± 3.5	0.94
Peak Cε (%)	0.5 ± 4.2**	0.97	0.5 ± 2.2	0.98
Peak Rε (%)	0.5 ± 15.6**	0.56*	1.4 ± 7.5	0.97
Peak Aε (%)	0.6 ± 3.8	0.99	0.6 ± 3.4	0.98
Inter-observer variability				
Peak Lε (%)	0.4 ± 3.0	0.91	1.0 ± 3.8	0.89
Peak Cε (%)	0.4 ± 10.4**	0.84	1.1 ± 3.9	0.91
Peak Rε (%)	4.8 ± 22.2**	0.44*	3.6 ± 8.0	0.90
Peak Aε (%)	0.3 ± 10.8**	0.92	1.7 ± 4.1	0.96
Test/re-test variability				
Peak Lε (%)	0.6 ± 5.4	0.84	0.5 ± 3.7	0.94
Peak Cε (%)	0.2 ± 9.6**	0.82***	0.0 ± 3.7	0.95
Peak Rε (%)	1.5 ± 14.8**	0.66*	0.9 ± 7.7	0.96
Peak Aε (%)	0.3 ± 8.8**	0.91	0.5 ± 4.1	0.98

Aε, area strain; Cε, circumferential strain; ICC, intra-class correlation; Lε, longitudinal strain; Rε, radial strain. Bias represents absolute (i.e. strain-percent) values.
*$P < 0.0001$, **$P < 0.001$, ***$P < 0.05$ for comparisons of coefficients of repeatability and of intra-class correlations.

Conclusions

Since peak strain values obtained from different ultrasound systems are not comparable, clinicians willing to translate 3D STE data from the literature into clinical decision making should take into account the specific system used in their echocardiographic laboratory and reference values of the strain components should be developed for each ultrasound system. Moreover, clinicians who want to use myocardial deformation parameters in longitudinal studies should ensure that baseline and follow-up acquisitions are obtained using the same platform. Since these are major limitations to the implementation of myocardial deformation parameters in the clinical practice and to the spread of the technique across echocardiographic laboratories, manufacturers are urged to take initiatives in order to overcome those variations and provide a common standard of two-dimensional and 3D strain measurement across vendors.

Table 5 Results of global 3D strain measurements and comparison between Artida and Vivid E9 platforms in a subset of 22 patients with good quality 3D data sets

Global ε (%) (*n* = 22)	Artida	Vivid E9	Bias	LOA	*r*
Longitudinal					
End systolic	−13.8 ± 4.6	−14.9 ± 4.7**	1.0	−3.1 to 5.2	0.888*
Peak	−14.1 ± 4.5	−15.6 ± 4.9**	1.5	−2.9 to 5.9	0.886*
Circumferential					
End systolic	−22.8 ± 8.7	−15.4 ± 5.5*	−7.4	−15.9 to 1.1	0.905*
Peak	−22.9 ± 8.7	−16.3 ± 5.7*	−6.6	−14.1 to 0.9	0.938*
Radial					
End systolic	16.1 ± 9.4	42.2 ± 15.8*	−26.0	1.1 to 53,2	0.486**
Peak	17.1 ± 8.8	44.3 ± 16.6*	−27.2	0.6 to 54.9	0.518**
Area					
Endsystolic	−34.1 ± 10.9	−27.1 ± 8.2**	−7.0	2.5 to −16.6	0.905*
Peak	−34.2 ± 10.9	−28.2 ± 8.6**	−6.0	2.5 to −14.5	0.928*

ε, strain; LOA, limits of agreement. Bias and LOA represent absolute (i.e. strain-percent) values.
*$P < 0.001$, **$P < 0.05$.

Table 6 Comparison of global 3D strain measurements (peak systolic) from data sets acquired at different temporal resolution with Artida

3D strain component ($n = 14$)	30 vps	20 vps	Bias ± SD	ICC	*t*-test
Peak Lε (%)	−14.3 ± 3.9	−12.9 ± 3.4	1.4 ± 2.0	0.852	0.52
Peak Cε (%)	−22.5 ± 5.5	−22.4 ± 4.4	0.1 ± 2.7	0.847	0.796
Peak Rε (%)	24.4 ± 8.0	21.2 ± 4.4	−3.2 ± 7.8	0.246	0.264
Peak Aε (%)	−33.8 ± 7.2	−33.1 ± 6.3	0.7 ± 3.1	0.892	0.423

Bias represents absolute (i.e. strain-percent) values.

Acknowledgements

The authors acknowledge the valuable contribution of Gianmarco Stucchi for the technical support offered in all the phases of the study.

Conflicts of interest: D.M. has received equipment and research funding from GE Healthcare. U.C., O.A.N., C.S., and S.I. have no conflicts of interest to disclose. L.P.B. has received equipment grants from GE Healthcare and is on the Speakers' Bureau of this company.

Funding

D.M. was supported by a Research Grant programme awarded by the European Association of Echocardiography.

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