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New speckle-tracking algorithm for right ventricular volume analysis from three-dimensional echocardiographic data sets: validation with cardiac magnetic resonance and comparison with the previous analysis tool

Denisa Muraru[1]*, Veronica Spadotto[1], Antonella Cecchetto[1], Gabriella Romeo[1], Patrizia Aruta[1], Davide Ermacora[1], Csaba Jenei[2], Umberto Cucchini[1], Sabino Iliceto[1], and Luigi P. Badano[1]

[1]Department of Cardiac, Thoracic and Vascular Sciences, University of Padua, Via Giustiniani 2, Padua 35128, Italy; and [2]Department of Cardiology and Cardiac Surgery, University of Debrecen, Debrecen, Hungary

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Aims (i) To validate a new software for right ventricular (RV) analysis by 3D echocardiography (3DE) against cardiac magnetic resonance (CMR); (ii) to assess the accuracy of different measurement approaches; and (iii) to explore any benefits vs. the previous software.

Methods and results We prospectively studied with 3DE and CMR 47 patients (14–82 years, 28 men) having a wide range of RV end-diastolic volumes (EDV 82–354 mL at CMR) and ejection fractions (EF 34–81%). Multi-beat RV 3DE data sets were independently analysed with the new software using both automated and manual editing options, as well as with the previous software. RV volume reproducibility was tested in 15 random patients. RV volumes and EF measurements by the new software had an excellent accuracy (bias ± SD: −15 ± 24 mL for EDV; 1.4 ± 4.9% for EF) and reproducibility compared with CMR, provided that the RV borders automatically tracked by software were systematically edited by operator. The automated analysis option underestimated the EDV, overestimated the ESV, and largely underestimated the EF (bias ± SD: −17 ± 10%). RV volumes measured with the new software using manual editing showed similar accuracy, but lower inter-observer variability and shorter analysis time (3–5′) in comparison with the previous software.

Conclusion Novel vendor-independent 3DE software enables an accurate, reproducible and faster quantitation of RV volumes and ejection fraction. Rather than optional, systematic verification of border tracking quality and manual editing are mandatory to ensure accurate 3DE measurements. These findings are relevant for echocardiography laboratories aiming to implement 3DE for RV analysis for both research and clinical purposes.

Keywords three-dimensional echocardiography • right ventricle • right ventricular function • magnetic resonance • validation • speckle tracking

Introduction

Right ventricular (RV) volumes and ejection fraction (EF) are independent determinants of patient clinical status and adverse outcome.[1–4] Given its complex shape, the quantification of RV geometry and function by conventional echocardiography remains challenging. Three-dimensional echocardiography (3DE) enables accurate and reproducible measurements of RV volumes and EF.[5]

* Corresponding author. Tel: +39 329 0491866; Fax: +39 049 8211802. E-mail: denisa.muraru@gmail.com

A meta-analysis of 23 studies published between 1997 and 2010 identified a systematic underestimation of RV volumes and EF by 3DE with respect to cardiac magnetic resonance (CMR), and highlighted several targets for further development of 3DE, such as matrix-array transducers, higher spatial and temporal resolution, and semi-automated tracking software for diseased RVs.[6] Over the last decade, 3DE underwent significant technological advancements in both hardware and software, image quality has visibly improved, and now 3DE is recommended for the routine clinical assessment of RV size and function.[5]

Recently, a new software based on speckle-tracking technology has been commercially released, enabling an automated 3DE quantitation of the RV with minimal human interaction. The rationale is that an automatic extraction and tracking of the RV endocardial contour throughout the cardiac cycle could further improve the accuracy and reproducibility of RV analysis, by eliminating the cumbersome manual tracing and editing of RV contours required by the previous software.[7]

Accordingly, this prospective study was designed to assess (i) the accuracy and reproducibility of the new 3DE software in relation to CMR in measuring RV volumes and EF; (ii) whether human intervention for adjusting the RV contours after automated border identification (optional) has any significant impact on the accuracy of the measurements; (iii) whether the new software provides additional benefits in comparison with the previously validated semi-automated software[6] in terms of accuracy, reproducibility, and time of analysis.

Methods

Study design

To address these aims, we studied 47 patients (46 $\pm$ 20 years of age, 27 men, body surface area of 1.83 $\pm$ 0.22 m^2) with a wide range of RV end-diastolic volumes (EDV = 82–354 mL at CMR) and function (EF = 34–81%). Patients were selected from 65 consecutive patients who were referred for clinically indicated echocardiogram and CMR, and had no contraindications for CMR (arrhythmias, inability to breathhold for 10–15 s, pacemaker or defibrillator, claustrophobia). The final cohort of 47 patients was obtained after excluding patients with: (i) an acute condition (acute myocardial infarction, acute myocarditis, etc), and in which CMR study was performed >24 h apart from the echo study due to logistical reasons ($n = 12$); (ii) inadequate apical acoustic window for RV quantitative assessment by two-dimensional (2D) echocardiography ($n = 4$); (iii) 3D data sets of inadequate quality, prohibiting the semi-automated RV analysis ($n = 2$). In 38 patients (81%), 3DE and CMR were performed within 24 h. The remaining 9 patients underwent 3DE and CMR from 4 to 19 days apart, while being in stable conditions, with no change in medical treatment or clinical status. Independent measurements were performed to assess the agreement of RV measurements by 3DE and CMR. The study was approved by the institutional Ethics committee. Written informed consent was obtained from all patients.

3D echocardiographic imaging

Four- or six-beat full-volume 3D data sets (32 $\pm$ 9 vol/s, range 20–55) were obtained during breathhold using Vivid E9 (GE Vingmed Ultrasound, Horten, Norway) equipped with 4V probe. The 12-slice display was used during acquisition to ensure a complete inclusion of the RV in the data set.[8] The 3D data sets were exported in VolDICOM format to a separate workstation equipped with the two vendor-independent software packages, i.e. new 4D RV-Function 2.0 (TomTec Imaging Systems GmbH, Unterschleissheim, Germany) and 4D RV-Function 1.2 (TomTec Imaging Systems GmbH, Unterschleissheim, Germany). A single experienced investigator (D.M.), who was blinded to the results of CMR analysis, performed the 3DE quantitation of RV volumes and EF with both software packages.

3D echocardiographic analysis

The image quality of 3D data sets was judged subjectively, considering the signal-to-noise ratio and the completeness of RV endocardium visualization, and was cathegorized on a scale from 1 to 4 (from poor to excellent). Image quality was judged as poor if ultrasound dropout was present in more than one half of the RV free wall in the coronal view.[9]

The 4D RV-Function 2.0 software works in several steps. After selecting the acquisition approach for the RV 3DE data set (transthoracic or transoesophageal, standard or customized), the operator aligns the 3D data set by setting the left ventricular (LV) and the RV longitudinal axes in the reference end-diastolic frame (*Figure 1* and see Supplementary data online, *Video S1*). On the LV apical long-axis view, the operator sets the landmarks corresponding to the aortic annulus diameter (AV1–AV2, *Figure 1*), and on the RV short-axis view, the anterior (AJL) and posterior junctions (PJL) of the RV free wall with the interventricular septum, and the septum-to-RV free wall distance are set. The software algorithm analyses ultrasound backscatter intensities and adapts a static RV shape model to all the input data, which can be further optimized by the operator. Then, the RV contours are automatically tracked over the entire cardiac cycle using the speckle-tracking technology, and automated measurements of RV volumes and EF are provided. Optionally, the operator can correct the RV contours identified by the algorithm, if necessary. Manual corrections on end-systolic and end-diastolic frames are continuously updated on the RV 3D model and then propagated to all the other frames of the cardiac cycle using the derived tracking information (*Figure 2* and see Supplementary data online, *Videos S2–S4*). RV volumes over time (*Figure 3* and see Supplementary data online, *Video S5*) are computed from the dynamic surface model, and maximal and minimal volumes are used to calculate EDV, ESV, EF, and stroke volume (SV). In addition to 3D volumetric measurements, the software derives standard 2D measurements on the four-chamber view obtained from the same 3DE data set; however, only RV volumes and EF measurements have been analysed herein.

In the present validation study, both the 'automated' method (i.e. no manual editing after automated tracking) and the 'manual editing' method (i.e. manual editing after automated tracking, systematically performed at both end-diastole and end-systole) (*Figure 2* and see Supplementary data online, *Video S4*) were used in all data sets for comparison. The manual editing was done so that the trabecular part of the RV wall, papillary muscles, and moderator band were part of the RV cavity (see Supplementary data online, *Videos S2–S4*).

A detailed description of the RV analysis using 4D RV-Function 2.0 software package has been included in the Supplementary data online.

The workflow of 4D RV-Function 1.2 (or 1.1) software has been described elsewhere.[7] This software uses a semi-automated border detection algorithm based on *in vivo* normal and pathologic RV models and was validated against CMR.[6,7,10] Briefly, the RV endocardium was manually traced in four-chamber, sagittal (short-axis), and coronal planes, at end-diastole and end-systole. Selection of end-diastolic and end-systolic frames was carried out manually. The alignment of the three planes required manipulation by slicing, rotating, and angulating in any of these three displayed orthogonal planes using a combination of software controls and mouse buttons. Manual corrections of semi-automatically

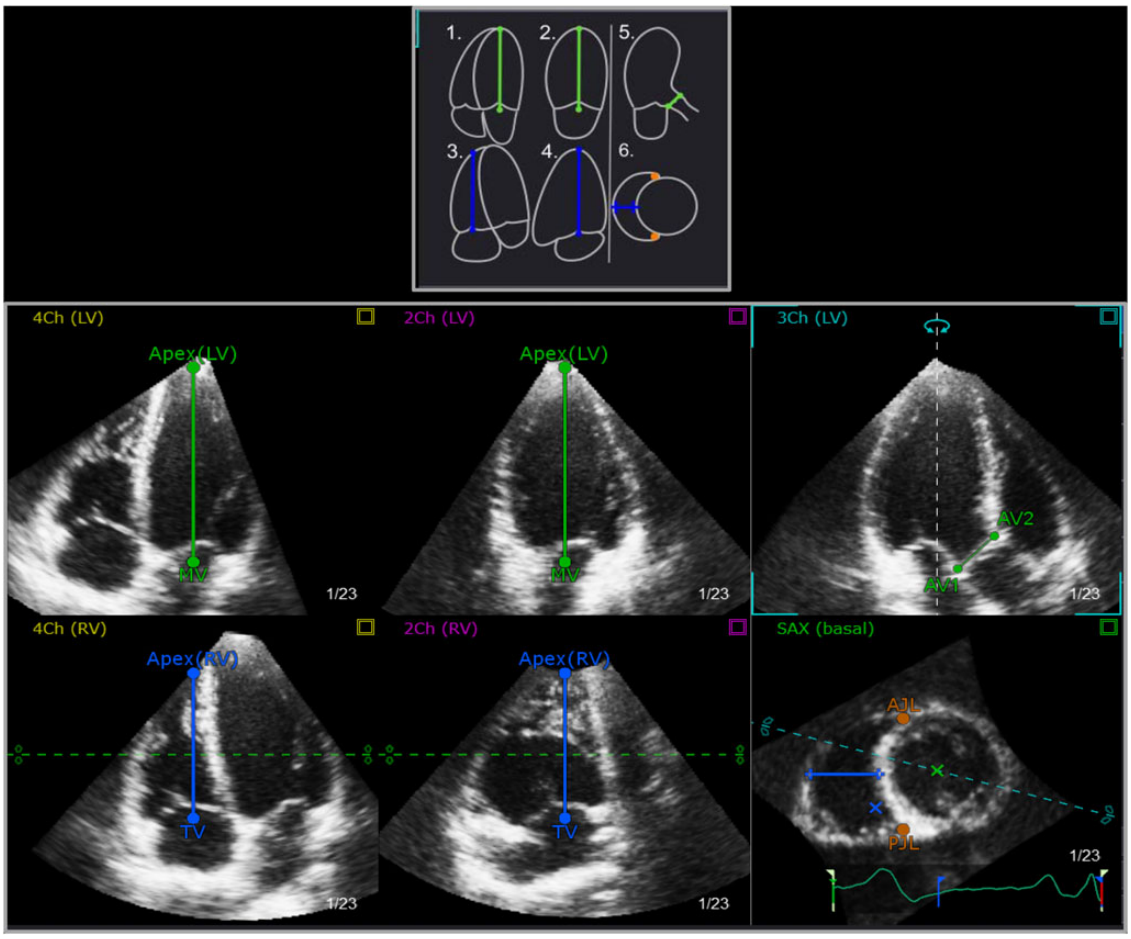

Figure 1 Alignment of 3D data set and identification of landmarks. On two orthogonal views of the left (LV) and right ventricle (RV), the position and the orientation of the green longitudinal markers were adjusted to obtain the conventional four-chamber (4-Ch) and two-chamber (2-Ch) views of LV and RV (Steps 1–4). Then, a LV apical long-axis view (3-Ch) could be visualized and optimized in the top far right image (Step 5), on which the aortic valve annulus diameter (AV1–AV2) was marked. Finally, on the RV short axis on bottom far right image (Step 6), the anterior (AJL) and posterior junction landmarks (PJL) and the septal-to-free wall distance were identified. TV, tricuspid valve; MV, mitral valve (see Supplementary data online, *Video S1*).

detected RV contours were systematically performed, so that the trabecular part of the RV wall, papillary muscles, and moderator band were part of the RV cavity. RV volumes were semi-automatically computed throughout the entire cardiac cycle, from which EDV, ESV, SV, and EF were calculated.

Magnetic resonance imaging

CMR images were obtained with a 1.5 T scanner (MAGNETOM Avanto, Siemens Medical Systems, Erlangen, Germany) with a phased-array cardiac coil. In each patient, ECG-gated, steady-state free precession (SSFP) cine sequences were acquired using 10- to 15-s breathholds. RV cine loops of 6–8 mm thick short-axis slices with no interslice gap were acquired from just above the ventricular base to just below the apex.

Magnetic resonance imaging analysis

CMR images were analysed using a commercial dedicated software (cvi[42] 4.1.8, Circle Cardiovascular Imaging Inc., Calgary, Canada). RV endocardial contours were traced manually on all short-axis slices and phases by investigators experienced in CMR analysis (V.S. and A.C.), who were blinded to 3DE measurements. Care was taken to include the papillary muscles, the tricuspid inflow, and the RV outflow tract within the RV cavity. The right atrium and pulmonary artery were avoided on the most basal slice.[11]

Reproducibility analysis

To determine the measurement reproducibility of the RV measurements for 3DE and CMR, image analysis was repeated in 15 randomly selected patients by a second investigator, as well as by the same primary investigator 1 week after the first analysis. During all repeated analyses, investigators were blinded to the results of the first RV measurements.

Statistical analysis

Continuous variables were summarized as mean ± SD, and cathegorical data were reported as percentages. 3DE-derived RV measurements obtained with both software packages were compared with the corresponding CMR values using linear regression with Pearson correlation

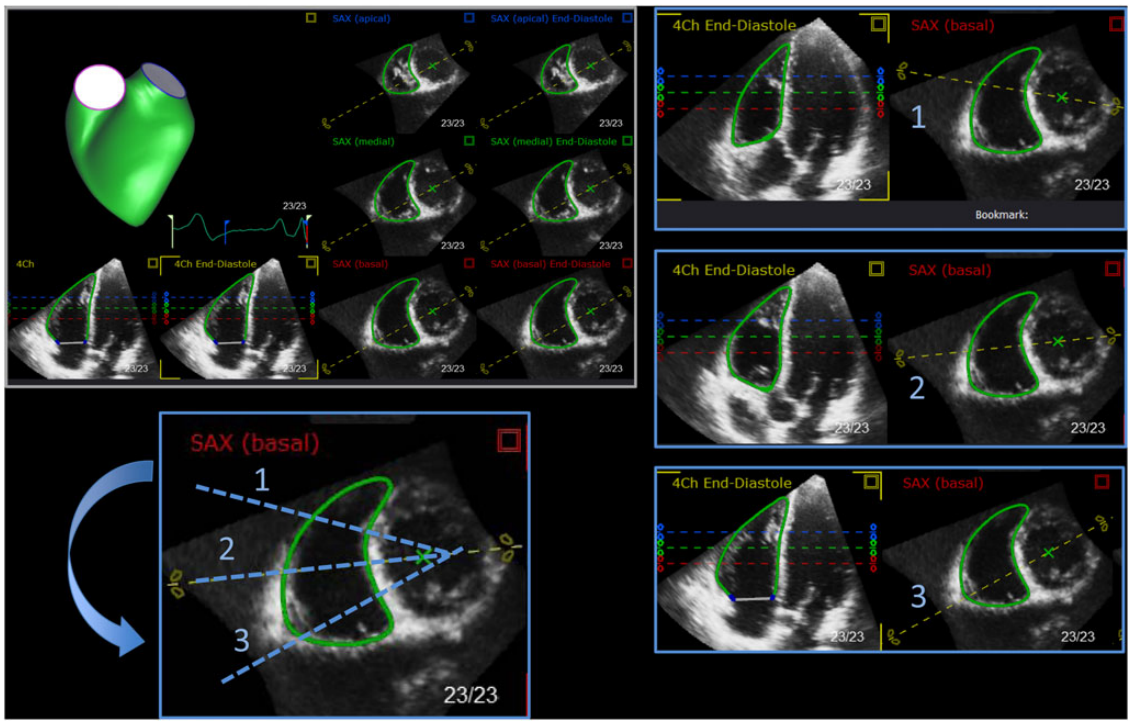

Figure 2 Verification and manual editing of endocardial contours. In a multi-slice display showing the RV four-chamber view and three short axes, verification of the accuracy of automated RV endocardial contour identification was done on both end-diastolic and end-systolic frames. The short-axis planes (dashed red, green, and dark blue lines) could be manually translated and long-axis plane (dashed yellow line) rotated, to ensure a thorough visualization of the endocardial borders including in between the pre-defined views displayed by the software (Panels 1–3). In regions where the green contour line did not match with the position of RV endocardium, the contour line was manually adjusted by clicking and dragging it with the mouse to the desired position (see Supplementary data online, *Videos S2–S4*).

coefficients and Bland–Altman analyses to assess the bias and limits of agreement. Paired *t*-test vs. null values was used to test the significance of the biases. The measurement variability (intra- and inter-observer) was assessed using Bland–Altman analysis and intraclass correlation. All analyses were performed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Differences among variables were considered significant at $P < 0.05$.

Results

The patient characteristics are outlined in *Table 1*. Image quality by 3DE data sets was graded as very good in 26% ($n = 12$), good in 38% ($n = 18$), fair in 28% ($n = 13$), and poor in 8% ($n = 4$) of patients.

Accuracy of 4D RV-Function 2.0 software vs. CMR

Three-dimensional echocardiography-derived values of RV volumes correlated tightly with the CMR values ($r = 0.92$ for both EDV and ESV, $P < 0.001$) (*Figure 4A–C*). Moreover, RV SV by 3DE had a close correlation with RV SV by CMR ($r = 0.90$, $P < 0.001$). Bland–Altman analysis revealed small negative biases of 15, 4, and 6 mL for EDV, ESV, and SV ($P < 0.001$ for all), reflecting a slight underestimation of RV volumes by the 3DE method. The limits of agreement (2SD) were in the range of 45 mL for EDV, 28 mL for ESV, and 23 mL for the SV. There was a positive relationship between the extent of EDV underestimation by 3DE and the RV size by CMR ($r = 0.44$, $P = 0.002$).

RV EF obtained by 3DE correlated well with the EF measured by CMR ($r = 0.86$, $P < 0.001$). On average, there was a negligible bias between 3DE- and CMR-derived EF of 1.4%, with limits of agreement within 10%.

Method comparison vs. CMR (impact of manual editing)

Figure 4A–C present the comparison between the 3DE analysis performed by automated method and by manual editing. Using the 4D RV-Function 2.0 with automated method, EF was largely underestimated ($-17 \pm 19\%$), as a consequence of EDV underestimation (-27 ± 54 mL) and ESV overestimation (10 ± 40 mL) with respect to CMR. In addition, the correlation of automated 3DE-derived RV EF with CMR EF was poor ($r = 0.36$, $P < 0.001$). Manual editing of RV endocardial contours significantly reduced the bias and strengthened the correlation of 3DE-derived RV measurements with CMR, particularly for EF.

Software comparison vs. CMR

As shown in *Table 2*, accuracy of measurements performed with 4D RV-Function 2.0 and 1.2 software algorithms vs. CMR were similar, providing that manual editing of endocardial borders was applied with both software packages.

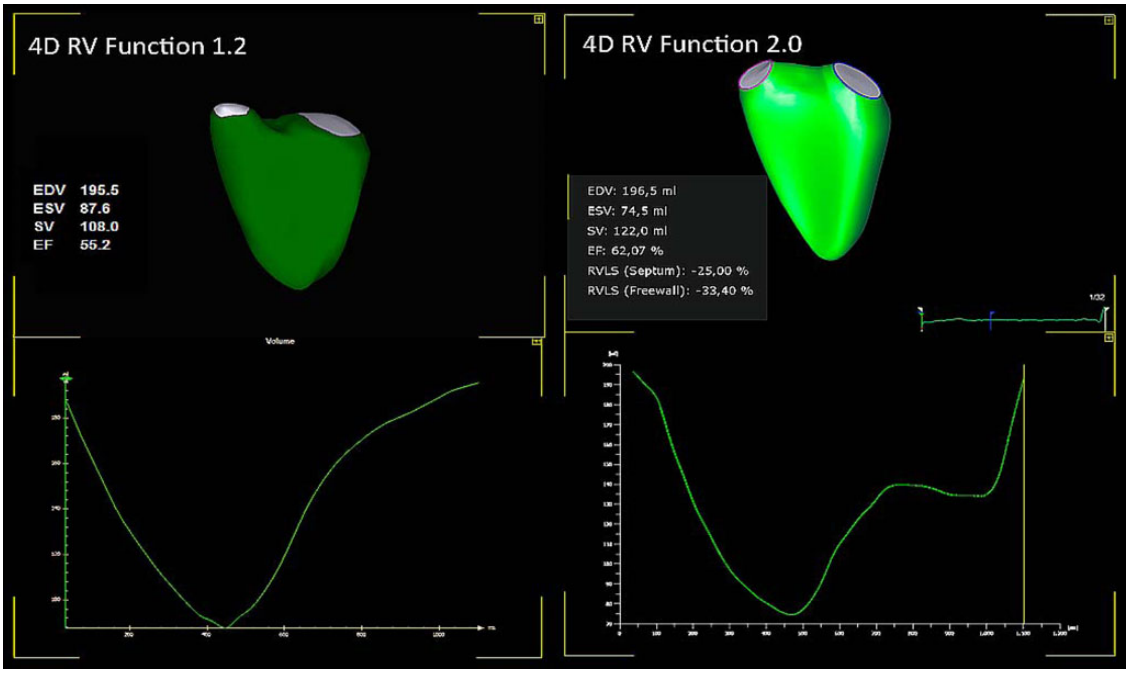

Figure 3 Examples of RV dynamic surface models obtained using the two software packages. The dynamic RV reconstruction allowed to compute the curves of RV 3D volumes over time, which are used to calculate end-diastolic (EDV) and end-systolic volumes (ESV), ejection fraction (EF), and stroke volume (SV). With previous software, the volume–time curve appears monophasic, while with the new software the RV filling appears to follow a more physiologic pattern (rapid filling, diastasis, and late filling after atrial contraction) (see Supplementary data online, *Video S5*).

Table 1 Patient characteristics ($n = 47$)

Characteristics	Value
Age (years)	46 ± 20 (range 14–82)
Men (%)	57
Body surface area (m^2)	1.83 ± 0.22
Body mass index (kg/m^2)	25 ± 4
Systolic blood pressure (mmHg)	120 ± 16
Diastolic blood pressure (mmHg)	73 ± 10
Heart rate (bpm)	66 ± 13
Indication for CMR (%)	
Ischaemic heart disease	43
Congenital heart disease	21
Cardiomyopathy	15
Myocarditis	4
Other	17

Data are expressed as mean ± standard deviation (range) or as percentages.
bpm, beats per minute; CMR, cardiac magnetic resonance.

Time of analysis

Using 4D-RV Function 2.0 with manual editing method required a longer analysis time (5 min; range 3–8 min) in comparison with the automated method (2 min; range 1–3 min). In data sets with good or excellent quality, the new software worked faster than the previous software (3–5 vs. 6–7 min). In data sets having fair or poor image quality, which required larger amounts of manual corrections of RV endocardial boundary, the analysis time required by the two software packages was comparable (6–8 min).

Reproducibility

The measurements obtained by the new 4D RV-Function 2.0 software showed an excellent reproducibility (*Table 3*), except for the inter-observer variability of EF which was higher than CMRs ($P < 0.05$). The new software also showed a better inter-observer reproducibility of RV volumes than the previous software (*Table 3*).

Discussion

This is the first prospective study validating a new speckle-tracking software dedicated for RV quantification from 3DE data sets against CMR. The main findings of this study can be summarized as follows: (i) RV volumes and EF measurements by the tested software showed an excellent accuracy and reproducibility, provided that the automatically tracked RV contours were systematically edited by the operator; (ii) The automated analysis option underestimated the EDV, overestimated the ESV, and largely underestimated the EF; and (iii) The new algorithm with manual editing showed similar accuracy, but lower inter-observer variability of RV volumes and faster analysis in good-quality 3DE data sets in comparison with the previous software.

The value of RV volumes and EF as powerful predictors of morbidity and mortality is well established.[12] 3DE quantitation of RV size

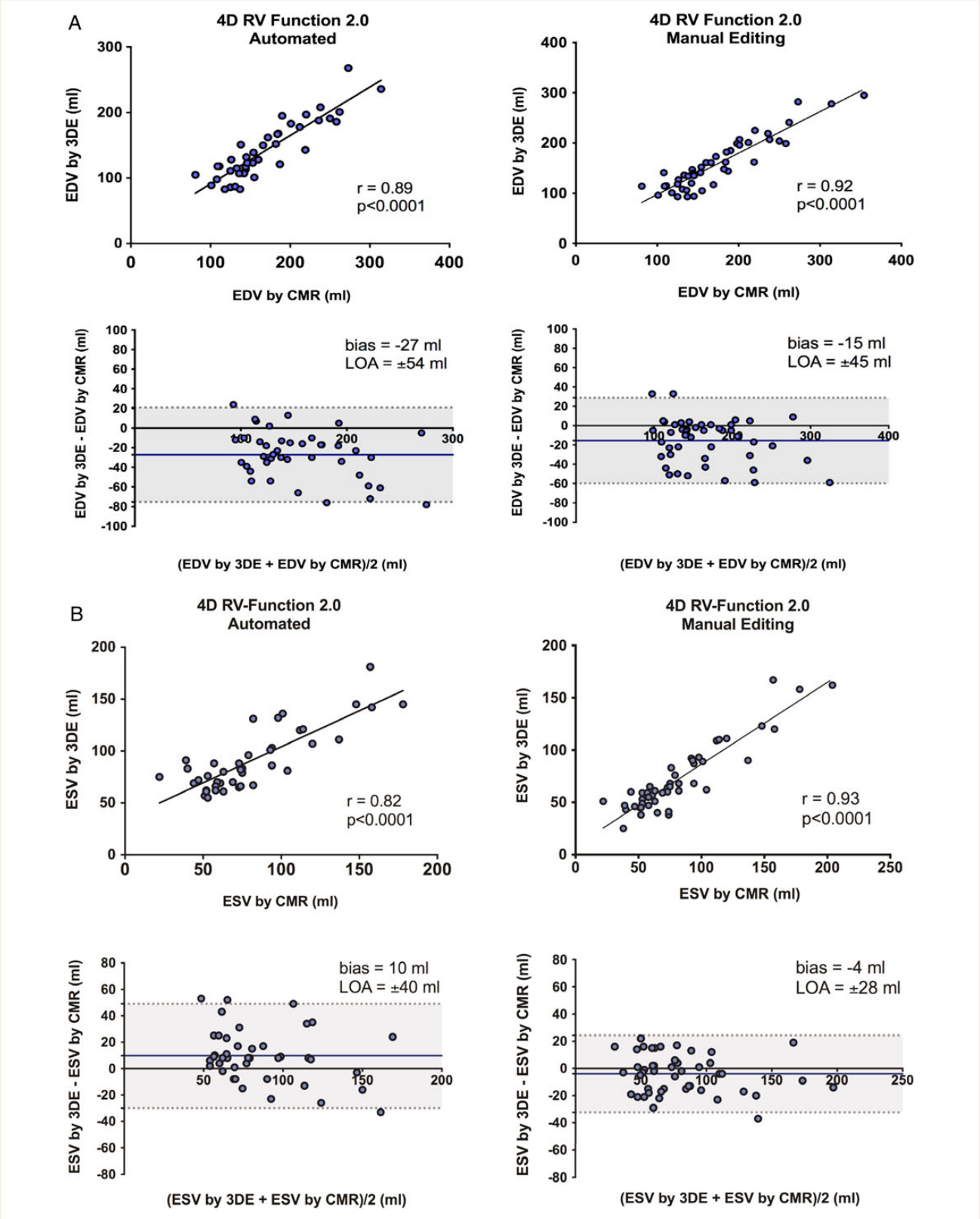

Figure 4 Accuracy of the new software algorithm vs. CMR for end-diastolic volume (EDV, *A*), end-systolic volume (ESV, *B*), and ejection fraction (EF, *C*) with comparison of two different options of analysis: manual editing vs. automated method. The manual editing method showed a greater accuracy than automated method for all RV parameters and for EF in particular.

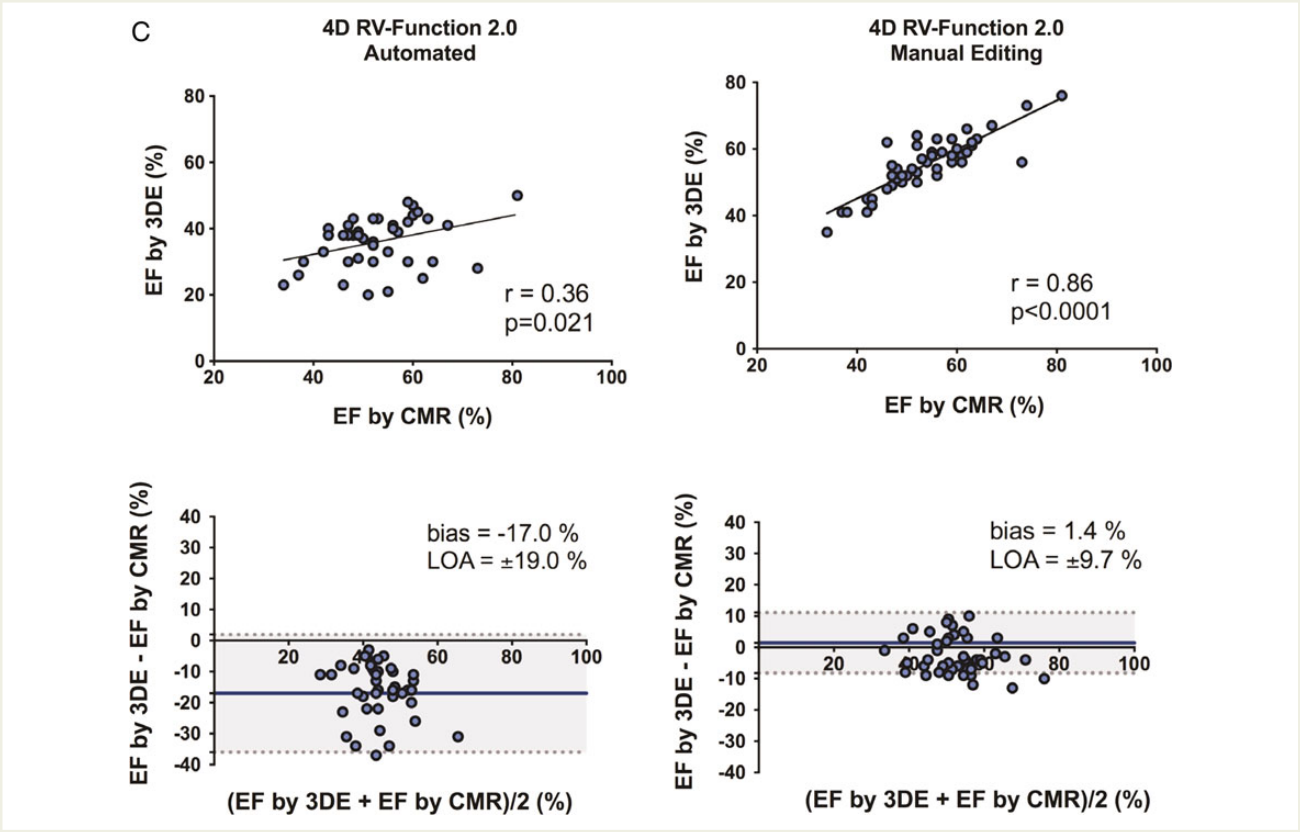

Figure 4 Continued.

Table 2 Comparison of the accuracy of RV measurements by 4D RV-Function 2.0 and by 4D RV-Function 1.2 vs. CMR

n = 47	EDV (mL)	ESV (mL)	EF (%)
4D RV-Function 2.0	−14 ± 45 (0.92)	−4 ± 28 (0.93)	1.4 ± 9.7 (0.86)
4D RV-Function 1.2	−19 ± 49 (0.90)	−10 ± 30 (0.92)	−2.9 ± 11.7 (0.80)

Values expressed as bias ± LOA (Pearson's correlation *r* coefficient).

and function is not affected by plane position error or unverified geometric assumptions, and therefore, it is more accurate and reproducible than conventional echocardiography indices when image quality is adequate.[13] Moreover, 3DE-derived RV systolic function has shown prognostic value,[14,15] and age- and gender-specific normative values of RV volumes and EF have been reported.[8] Accordingly, the current guidelines on cardiac chamber quantification state that any echocardiography laboratory with proper 3DE equipment and expertise should consider using 3DE to assess RV size and function.[5]

While all 3DE vendors have provided their own algorithms for LV quantitation, the more challenging RV analysis from 3D datasets has been performed in the past 7 years using a single vendor-independent semi-automated software (i.e. 4D-RV Function 1.1/1.2 by TomTec).[6] On one hand, this allowed researchers to rapidly gather solid evidence on its reliability based on a unifying methodology, but on the other hand, it contributed to a limited clinical applicability due to its time consuming nature and rather difficult workflow, requiring specific training.

Before its adoption, any further development of the RV software algorithm requires a rigorous validation work and a head-to-head comparison with the previous tool to verify: (i) whether the new software is reliable enough to replace the previous one; (ii) whether the clinical evidence and normative values obtained by the previous software can be extrapolated to RV measurements obtained by the new software.

In our study, the agreement of the new software with CMR was very similar with the agreement of previous software applied in the same population and reported by other studies.[6] In line with previous RV and LV studies,[6,16] we showed that 3DE yields volumes that are slightly, yet systematically smaller in comparison with those provided by CMR, while the EF is very similar between the two modalities. There was a trend for a superior accuracy of the new vs. old software with respect to CMR. The relatively limited sample size coupled with the ample spectrum of RV size and image quality of our patients might have played a role in the failure to reach the statistical significance. However, improvements of novel quantification tools in terms of reproducibility, usability, and time required for

Table 3 Results of reproducibility analysis evaluated using intraclass correlation (ICC) and Bland–Altman (BA) analysis between repeated measurements

n = 15	EDV (mL)	ESV (mL)	EF (%)
Intra-observer			
4D RV-Function 1.2	2.5 ± 13.9* (0.94*)	1.9 ± 11.0* (0.93*)	1.5 ± 5.8 (0.91)
4D RV-Function 2.0	2.9 ± 8.9 (0.98)	1.7 ± 8.2 (0.97)	0.4 ± 3.6 (0.93)
CMR	1.5 ± 7.6 (0.99)	1.5 ± 5.6 (0.99)	0.2 ± 3.5 (0.94)
Inter-observer			
4D RV-Function 1.2	0.9 ± 15.5*,† (0.92)	2.2 ± 15.0*,† (0.81*)	0.9 ± 7.4* (0.75*)
4D RV-Function 2.0	5.2 ± 8.8 (0.96)	7.0 ± 9.0 (0.93)	0.4 ± 6.9* (0.81)
CMR	0.3 ± 8.0 (0.98)	1.0 ± 6.5 (0.98)	0.9 ± 3.8 (0.93)

Values expressed as bias ± SD (ICC).
*$P < 0.05$ vs CMR.
†$P < 0.05$ vs RV-Function 2.0.

analysis (without any significant loss in accuracy) are also key aspects for the clinical implementation of 3D echocardiography for RV quantification. The added value regarding a superior inter-observer reproducibility of RV volumes and faster analysis could be explained by several features of the new software workflow, such as (i) the rapid automated identification of RV endocardial borders, reducing the analysis time and the inherent errors related to manual tracing of endocardium on several still frames; (ii) the removal of coronal view, deemed as the most challenging to trace even by experienced users; (iii) the flexibility in the selection of the most appropriate display of RV views; (iv) the fact that manual corrections are required only on end-systolic and end-diastolic frames, being continuously updated on the RV 3D model (*Table 4*, see Supplementary data online). In contrast, the previous software required manual corrections to be applied frame-by-frame, resulting in a 'fluttering' RV model, in which the fidelity of adopted corrections was difficult to predict or verify. In practice, these issues led to an inconsistent use of manual corrections ('when necessary'),[9,17] despite some evidence showing that manual corrections of automated RV contours are actually needed to ensure accurate measurements.[18]

As high-performing border-identification algorithms—close to a fully automated analysis—are now commercially available, the issue of the actual need of human input becomes clinically relevant. In line with a previous study,[18] we documented a lower accuracy of RV measurements when automated method was applied in ventricles of different geometry and image quality, in comparison with the manual editing method. In a previous paper, we have also demonstrated that manual editing yields more accurate LV 3DE volumes than automated analysis.[19] If one takes into account the many challenges of the RV in comparison with the LV (thinner and more trabeculated wall, complex and highly variable shape among pathologies and from patient to patient, separated inflow and outflow tracts, very active excursion, and tilting of lateral tricuspid annulus), our finding that systematic manual editing is needed to ensure accurate 3DE measurements for RV is not so surprising. Despite automated algorithms are more effective than humans at repetitive tasks, and extremely predictable and reproducible when applied on the same data sets, they are also highly dependent on the image quality and cannot react as well as a human operator in unusual circumstances.[20] The automated algorithms perform poorly in regions where endocardial boundaries are inadequately defined, have complex shape, or assume different geometry that predicted. Moreover, they do not make a reliable distinction between the compacted myocardium, which should be left outside the cavity tracing, and the papillary muscles, trabeculae, moderator band, etc, which should be included inside the cavity tracing. In all our data sets, we have made manual corrections to adequately include the prominent trabecular part of the wall inside the RV cavity. In regions where endocardium on still frame was poorly defined, we have systematically checked its position on magnified views in motion displayed side by side with the reference frame and also on the corresponding orthogonal slice showing the same region (see Supplementary data online). Moreover, we have noted that in some data sets from patients with normal RV function, the software did not track optimally the rapid descent of proximal basal part of the RV inflow in systole (*Figure 5*). Tracking problems were also seen in the proximity of the RV outflow tract, and they were not apparent in the standard four-chamber view displayed by the software. These observations emphasize the need to use systematically all the software controls available (*Figure 2* and see Supplementary data online, *Videos S2–S4*) to make a thorough verification of endocardial tracking quality and make the necessary adjustments.

Although the operator intervened in the analysis with the manual corrections of RV borders, we have shown that this did not affect the reproducibility of measurements, provided that the manual verification and correction of RV contours is always carried out according to the same principles (see Supplementary data online). Indeed, the inter-observer reproducibility of RV volume measurements was improved with respect to the previous software, and the intra-observer reproducibility was comparable with the manual measurements on CMR images. The reproducibility ranges in our study were comparable or superior with respect to previous studies.[7,10,17]

Clinical implications

Despite the very similar marketing names, the two RV software packages are quite different and characterized by a number of

Table 4 Comparison of the main features of the new software for RV 3D analysis vs. the previous software package

Characteristics	4D RV-Function 1.2	4D RV-Function 2.0 (new)
Views displayed	4Ch RV SAX (sagittal) coronal (RV inflow–outflow)	4Ch LV; 4Ch RV 2Ch LV; 2Ch RV 3Ch LV; SAX
Reference frame(s)	ED (adjustable) ES (adjustable)	Reference frame (adjustable) ED; ES (not adjustable, identified by the software from the volume/time curve)
Data set alignment	More user dependent	More automated
Mouse controls	Left and right buttons	Left button
Software controls	8 controls (rotation of view) 1 control (SAX translation)	
Landmarks	TV, MV, LV apex	TV, MV, LV apex RV apex, AA, AJL, PJL, septal-to-free wall distance
RV contour identification	Manual tracing (3 steps, 6 images)	Automated
Editing	Optional	Optional
Editable views	4Ch, SAX, coronal	4Ch, SAX
Views with adjustable plane position	SAX	4Ch, SAX
Nr. of frames required for editing	All frames (nr. depending on the VR)	ED, ES
Update of RV model	At the end of editing	Continuously
Editing of RV contour in the initialization steps	If edited in one view, manual contour tracing needs to be done again in all subsequent views	N/A
RV model	Possible failure in RV model reconstruction, if inconsistent manual tracings of RV in the three views	Automated RV model
RV measurements	EDV, ESV, EF, SV	EDV, ESV, EF, SV RVLS (septum and free wall) FAC, tricuspid annulus longitudinal displacement (4Ch) Diameters and areas (4Ch)
	Manual measurements for structures within the displayed RV views[a]	Manual measurements customizable for structures within the entire 3D dataset
Display	RV dynamic model (beutel) Volume/time curve	RV dynamic model (beutel) Volume/time curve

4Ch, four-chamber view; AA, aortic annulus; AJL, anterior junction landmark; ED, end-diastole; EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction; ES, end-systole; FAC, fractional area change; LV, left ventricular; MV, mitral valve; nr., number; PJL, posterior junction landmark; RV, right ventricular; RVLS, right ventricular longitudinal strain; SAX, short axis; SV, stroke volume; TV, tricuspid valve; VR, volume rate.
[a]Availability depends on the software version.

differences in terms of algorithm, workflow, display, contour editing, and measurement output. However, when tested in a clinical setting, they showed a similar accuracy for RV volumes and EF measurements. Our findings suggest that the previous evidence on the benefits of 3DE may hold true, irrespective of which of the two RV software packages is available in the echocardiographic laboratory. Importantly, the clinical implementation of the new software does not require different normative values for 3D RV volumes and EF than the existing ones.[5] Laboratories aiming to start implementing 3DE in the clinical routine may choose the more user-friendly and faster approach to RV quantitation provided by the new software, while laboratories with established experience with the previous RV software can use either of the two, or both. Clinicians using the new software should be aware of the risk of underestimating RV size and EF if the automated measurements have not been adequately validated and corrected by the operator. Advantages provided by the new software in terms of superior reproducibility, usability, and time required for analysis could be beneficial particularly for those patients requiring a close follow-up of RV volumes and function, that cannot be evaluated by serial CMR studies.

Limitations

This was a single-centre study involving a selected population, based on several criteria required to ensure the feasibility and the comparability of the 3DE and CMR examinations. Similarly with the vast majority of studies validating 3DE for chamber quantification, we have used CMR as reference method, despite we are aware that it is a tomographic method requiring manual tracings on several short axes, and therefore, it may not be a true 'gold standard' for RV volume quantification.[19] The proportion of dysfunctional RVs was rather small, but the challenges of speckle-tracking algorithms are more related to enlarged ventricles (with incomplete visualization and lower

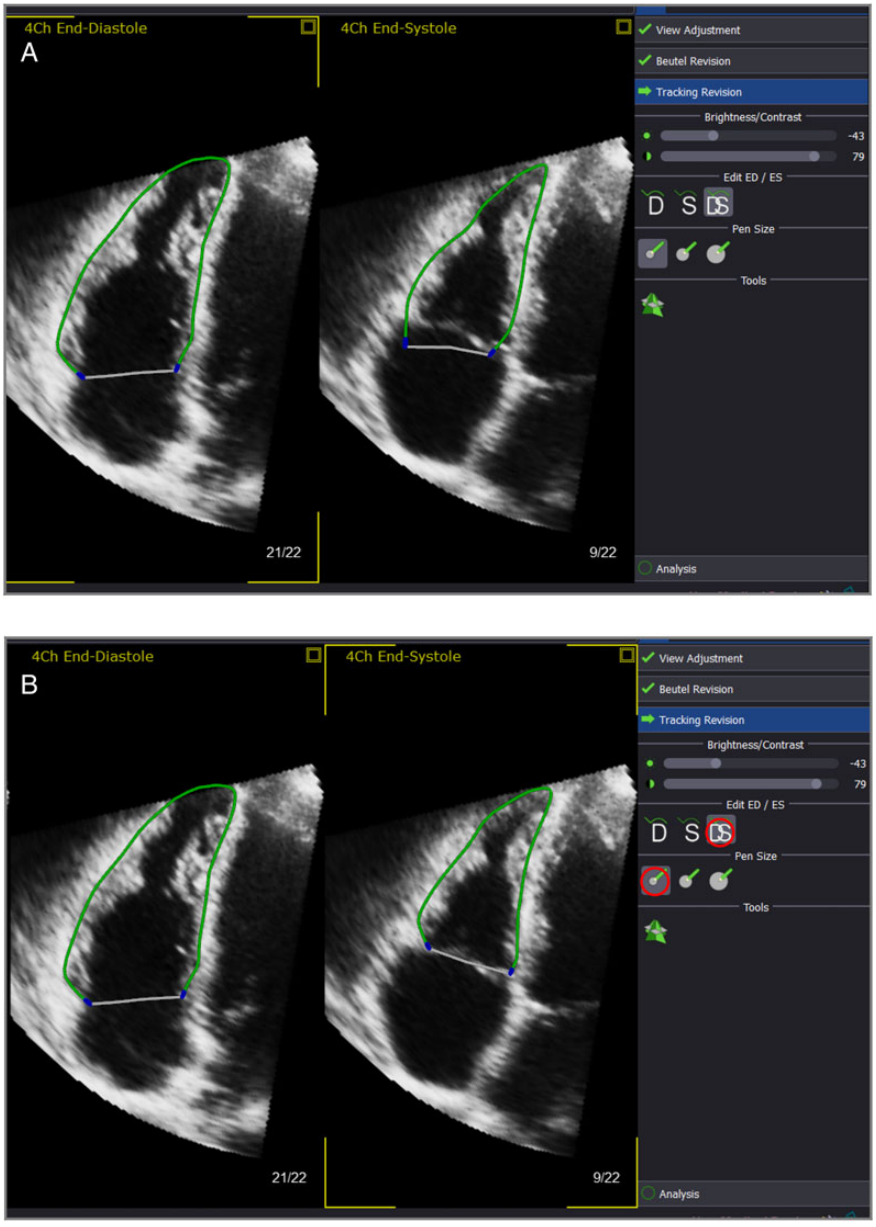

Figure 5 Example of suboptimal endocardial tracking of automated algorithm at end-systole (*A*). *Figure 5B* shows the RV contours after manual corrections on the end-systolic frame. At the right part of the screen, the settings that have been used for editing are shown: dual end-diastole/end-systole (DS) layout; smallest editing tool (pen).

temporal resolution) and to myocardial regions showing very large and rapid systolic excursions (more difficult to track through end-systole). Since our study was designed to validate a new software against CMR and compare it against the previous one, we have not evaluated the test–retest repeatability of RV 3DE measurements, as it depends much more on differences in data set acquisition, rather than in software analysis. The removal of coronal view from the workflow could be also regarded as a potential limitation of this software in analysing certain pathologies evolving with predominant RV outflow dilation/aneurysms. Despite our study included patients with different RV sizes and function, there were no aneurysms of RV outflow, and the relatively small proportion of congenital heart disease or arrhythmogenic cardiomyopathy did not allow us to evaluate more in depth for this aspect. Future studies including large samples from these pathologies are needed to address this concern.

Conclusions

Novel vendor-independent 3DE algorithm enables an accurate quantitation of RV size and function, a shorter analysis time, and a superior inter-observer reproducibility of RV volumes in comparison with the previous software. Rather than optional, the systematic verification of border tracking quality and manual editing are mandatory to ensure accurate 3DE measurements. These findings are

relevant for echocardiography laboratories aiming to implement 3DE for RV volume and EF analysis for both research and clinical purposes.

Supplementary data

Supplementary data are available at *European Heart Journal—Cardiovascular Imaging* online.

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