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ORIGINAL PAPER

Multi-parametric "on board" evaluation of right ventricular function using three-dimensional echocardiography: feasibility and comparison to traditional two-and three dimensional echocardiographic measurements

Gloria Tamborini[1] · Claudia Cefalù[1] · Fabrizio Celeste[1] · Laura Fusini[1] · Anna Garlaschè[1] · Manuela Muratori[1] · Sarah Ghulam Ali[1] · Paola Gripari[1] · Giovanni Berna[1] · Mauro Pepi[1]

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Abstract
Three-dimensional echocardiographic (3DE) of right ventricle (RV) has been validated in many clinical settings. However, the necessity of complicated and off–line dedicated software has reduced its diffusion. A new simplified "on board" 3DE software (OB) has been developed to obtain RV volumes and ejection fraction (EF) together with several conventional parameters automatically derived from 3DE: tricuspid annular plane systolic excursion (TAPSE), fractional area change (FAC), longitudinal strain (LS). Aims of this study were to evaluate feasibility and accuracy of OB RV analysis. A complete 2DE and 3DE with OB 3DRV evaluation was obtained in 35 normal subjects and 105 patients with different pathologies. Results were compared with the conventional off-line software (OFL) and with the 2D-derived corresponding values. A subgroup of 22 patients underwent also cardiac CMR. OB 3DRV was feasible in 133/140 cases (95%) in a mean time of 97.5 ± 33 s lower than OFL analysis (129 ± 52 s plus dataset loading 80 ± 24 s). Imaging quality was good in 84%. OB and OFL 3DE RV volumes and EF were similar. 3DE derived FSA and LS (but not TAPSE) were similar to 2DE values and correlated with tissue Doppler systolic peak velocity, dP/dt, systolic pulmonary pressure and myocardial performance index. OB RV volumes and EF well correlated with CMR. (bias + SD: − 21.5 ± 20 mL for EDV; − 8.2 ± 12.4 mL for ESV; − 1 ± 5.9% for EF). OB 3DE method is feasible, simple, time saving. It easily provides 3DE RV volumes and multiple functional parameters. Off-line operator border adjustment may improve accuracy of 3DE TAPSE.

Keywords Three-dimensional echocardiography · Right ventricle · Right ventricular ejection fraction · Right ventricular strain

Introduction

The importance of an accurate right ventricle (RV) volume and function estimation in most of cardiac diseases has been extensively demonstrated [1–4]. Unfortunately, due to the peculiar RV morphology, limitations of 2 dimensional echocardiography (2DE) are well known and therefore 3 dimensional echocardiography (3DE) has been proposed and validated for RV volume quantification in many clinical settings [7–14]. However, the necessity of complicated and off line dedicated software, [5, 6, 15] has reduced the diffusion of 3DE RV evaluation in daily practice.

Moreover, since RV performance is more sensitive to increases in after load in comparison with left ventricle [LV], most of RV functional echocardiographic indexes are strictly influenced by load changes [10, 16, 17] and the combination of multiple functional indexes such as tricuspid annular plane systolic excursion (TAPSE), fractional area change (FAC) and longitudinal strain (LS) with the addition of RV ejection fraction (EF) may significantly improve diagnostic accuracy and prognostic value in various RV and LV pathological conditions [18, 19]. Recently, a simplified 3DE software has been developed for echocardiographic RV analysis [20, 21], now available on board and able to compute RV end-diastolic (EDV) and end-systolic (ESV)

✉ Gloria Tamborini
gloria.tamborini@ccfm.it

[1] Centro Cardiologico Monzino IRCCS, Via Parea 4, 20138 Milan, Italy

volumes, RV EF, TAPSE, FAC, free-wall and septal LS automatically derived from 3DE.

The aim of this study was twofold: (a) to evaluate the feasibility of this new software in a large population of normal and pathological subjects and the accuracy (in a subgroup of patients) to wards CMR. (b) to compare OB 3DE and correlate the results with the conventional 3DE methods and with the 2DE derived RV functional parameters.

Methods

Study population and design

In this prospective study population consisted of 154 consecutive patients referred for transthoracic echocardiography in our laboratory from November 2017 to May 2018. Exclusion criteria were the presence of atrial fibrillation (10 patients) or inadequate echocardiographic apical window (4 subjects). Thus 140 subjects were included in study population.

Subjects were divided into 2 groups. The first group consisted of 35 normal controls with no echocardiographic evidence of heart or valvular disease who underwent transthoracic echocardiography for atypical chest pain, palpitations or innocent cardiac murmurs. The second group consisted of 105 patients with clinical or echocardiographic evidence of cardiac disease: valvular heart disease (26 cases), coronary artery disease (20 cases) idiopathic dilated cardiomyopathy (33 cases), congenital or acquired pathologies associated with RV pressure or volume overload (26 cases). Each patient underwent a complete 2DE and 3DE.

The study protocol conformed to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a priori approval by the institution's human research committee and was approved by the institutional review board. An informed consent was obtained from each patient.

Two-dimensional echocardiography

All echocardiographic examinations were performed using a GE vivid E95 echocardiographic system (GE Vingmed, Horten, Norway) equipped with M5Sc-D probe. Complete standard 2DE was performed according to clinical laboratory practice (13).

LV EDV, ESV and biplane EF were measured from the 4-and 2-chamber views using the Simpson's method.

Two dimensional e Doppler-echo traditional RV functional parameters as FAC, TAPSE, Doppler peak systolic velocity (PSV) myocardial performance index (MPI), dP/dT, non invasive calculation of systolic pulmonary pressure (SPP) and 3-segment and 6-segment model longitudinal strain (LS) were measured according with international guidelines (16,22).

Three-dimensional echocardiography

Real-time 3DE imaging was performed at the end of the 2DE examination using the same ultrasound unit and the 4V-D probe. From the 4-chamber apical view adapted to improve the visualization of the RV, two consecutive acquisitions were obtained, gathered over 4 consecutive cardiac cycles in full-volume mode to ensure optimal temporal and spatial resolution at a frame rate of 25–30 frames/s. Multibeat image acquisition was performed while the patient's breath was held to eliminate breathing-related motion artifacts. The volumetric data sets were immediately analyzed with the dedicated on-line software 4D RV-Function 2.0 (Tom-Tec Imaging Systems GmbH, Unterschleissheim, Germany) and also digitally stored and then transferred into a workstation for offline post-processing analysis with the same dedicated system. This vendor-independent software has been validated against cardiovascular magnetic resonance (CMR) and its workflow has been extensively described elsewhere [20, 21].

Briefly the software automatically extracts from the acquired 3DE dataset the left and right ventricular apical 2- and 4-chamber views for manual LV and RV long axis alignment, left ventricular apical 3-chamber view for LV out flow diameter definition and a short-axis view to correctly identify the anterior and posterior junction points of the RV free wall with the interventricular septum and the longest dimension of the RV cavity between the septum and the free wall.

These anatomic landmarks are used to automatically extract the RV 4 chamber view and 3 sequential short-axis views from base to apex for both end-systole and end-diastole, the obtained RV 3DE endocardial surface is tracked throughout the cardiac cycle for 3DE RV reconstruction and 3DE volumes over time were then numerically computed from the dynamic surface model and used to determine EDV, ESV, and EF. In addition to 3DE volumetric measurements, the software derives standard 2DE measurements on the 4-chamber view extracted from the 3DE data set: TAPSE, FAC and septal and free wall LS. Operator border adjustments of automatic results may be performed if necessary.

The quality of 3-dimensional RV OB reconstruction, judged on the basis of RV morphology and the presence or absence of artifacts throughout the cardiac cycle, was rated as optimal or good (without artifacts and optimal or well defined RV end-diastolic and end-systolic endocardium) sufficient (with artifacts during the cardiac cycle but with well-defined RV morphology), or insufficient (with artifacts and irregular RV morphology).

CMR protocol

In 22 patients for specific clinical reasons and diagnostic indications, CMR was performed using a 1.5-T scanner (Discovery MR450; GE Healthcare, Milwaukee, WI) within 2 days of the echocardiographic examination. After the acquisition of localizer images of the heart, breath-hold steady-state free precession cine acquisitions were acquired using the following parameters: echo time 1.57 ms, 15 segments, repetition time 46 ms without view sharing, slice thickness 8 mm, field of view 350×263 mm, and pixel size 1.4×2.2 mm. CMR data were transferred to a dedicated workstation and analyzed using dedicated cardiac software (Report Card 4.0; GE Healthcare). RV EDV, ESV, and EF were evaluated on cine images according to the recommendations of the Society of Cardiovascular Magnetic Resonance.

Statistical analysis

Results are represented as mean and standard deviation.

Linear correlation and Bland–Altman analysis were utilized to compare OB 3DE RV volumes and EF with OFL values, obtained by the same operator in all the patients in a different day and to compare OB and OFL RV volumes and EF with CMR results. A value of $p < 0.05$ was considered to be significant.

Correlations and Bland Altman analysis were performed also between 3DE derived FAC, TAPSE, 3—segment model LS (free wall LS), 6—segment model LS (as the mean value of free wall plus septal LS) and the conventional 2DE derived corresponding functional parameters.

Reproducibility of the 3DE RV volumes was assessed in a randomly chosen subgroup of 20 patients. Intra-observer variability was assessed using repeated OB measurements performed by the same observer in a different day, while inter-observer variability was evaluated by repeating the OB analysis by a second independent observer, blinded to the results of all prior measurements. Variability was expressed in terms of coefficients of variation between repeated measurements as a percentage of their mean. Moreover, Bland–Altman analysis was applied to evaluate the limits of intra-observer and inter-observer agreement.

The sample size of 130 patients has been estimated as necessary to assess agreement between two methods of measurement at a significance level of 5% and at least 80% power with an acceptable allowed difference between the methods (EDV, 28.8 mL; ESV, 18.2 mL; EF, 13.6%).

Results

At least one good 3DE acquisition (without artifacts) of the RV was achieved in all 140 subjects in a mean time 74 ± 24 s. Despite satisfactory acquisition, the quality of 3DE RV reconstruction was insufficient in 7 patients (2 dilated cardiomyopathy, 4 RV disease with RV volumes > 300 mL and 1 coronary artery disease). Thus the feasibility of OB RV reconstruction was 95%. A Flowchart of selection process for study population is shown in Fig. 1. Imaging quality was

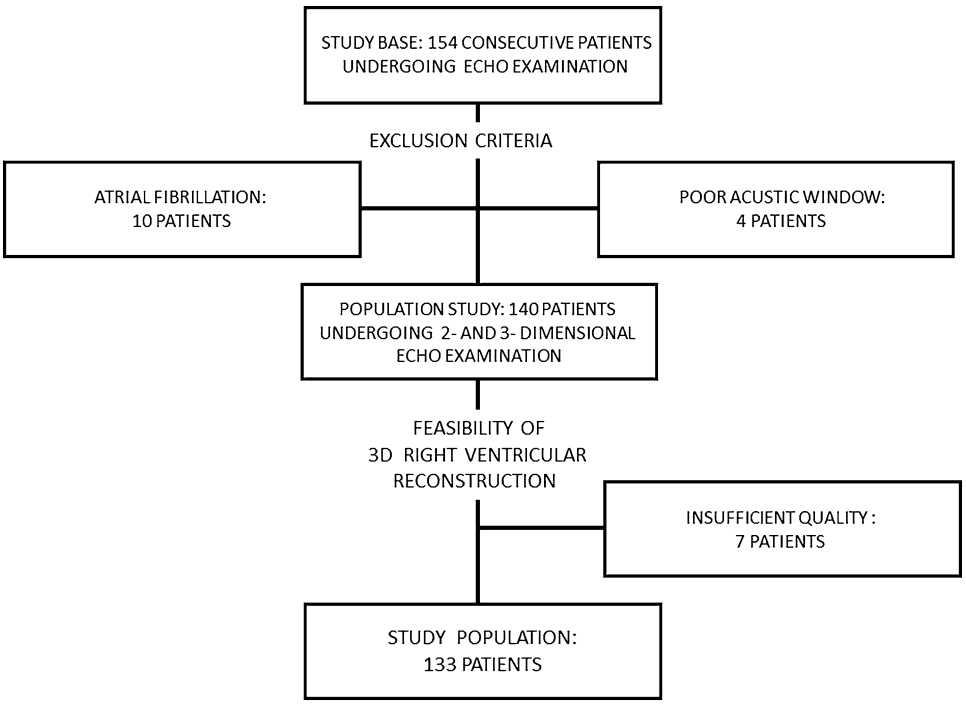

Fig. 1 Flowchart of selection process for study population. One hundred fifty-four consecutive patients underwent to an echocardiographic examination. Due to exclusion criteria (atrial fibrillation and poor acoustic windows) 14 patients were not enrolled. Of the remain 140 subjects (final study population) in 7 subjects 3D right ventricular reconstruction was judged not sufficient. Therefore final studied population consisted of 133 patients

optimal (40.7%) or good (41.4%) in most of them and sufficient in 12.8% of the cases.

The mean time for 3DE reconstruction was 97 ± 33 s for OB and 129 ± 52 s for OFL analysis (which allows more operator border adjustments of automatic results) in addition to 80 ± 24 s for RV dataset loading on the dedicated computer. Figure 2 shows two examples of 3-dimensional RV reconstruction in a normal subject and in a pathologic patient.

Demographic, 2DE and 3DE characteristics of the 133 patients finally included in the study are listed in Table 1: all 3DE RV volumes and functional derived parameters were significantly different in normal versus pathological patients.

Despite the overlapping of values, due to the various pathologies included in study population, not necessarily associated with RV dysfunction, the pathologic group was characterized by larger RV volumes and lower RV functional indexes No normal subject had RV EF < 47%, FAC < 38% or free wall LS < − 23%. On the contrary 2 normal cases had a value of 3DE 6-segment LS < − 17% and 7 cases a 3DE derived TAPSE < 17 mm (Fig. 3).

Comparing OB and OFL 3DE RV volumes and RVEF, no significant differences were observed (Table 2). Moreover OB 3DE derived function parameters FAC, 3 segment LS and 6-segment LS were not different in comparison with 2DE traditional corresponding measurements. On the contrary 3DE significantly underestimates TAPSE in comparison with M-Mode 2DE. The results of Bland Altman analysis between these parameters are shown in Figs. 4 and 5.

In our study population, 3DE RV EF, FAC, 3- and 6-segment LS positively correlated ($p < 0.001$) with RV dP/dt, PSV and negatively with SPP and MPI. Three-dimensional derived TAPSE showed a significant positive correlation with MPI and DTIs and a weak correlation with dP/dt ($p < 0{,}036$), while no correlation with SPP was observed (Table 3).

In the 22 patients who underwent CMR, OB RV volumes and EF correlated tightly with the CMR values likewise OFL RV results. The results of Bland–Altman analysis of the agreement between the two different 3DE methods and CMR measurements of EDV, ESV and EF are depicted in Table 4.

Intra-observer variability of 3DE RV measurements of EDV, ESV and EF as coefficient of variation were 2.9%, 4.2% and 3.7% respectively, while inter-observer variability of the same measures was 3.1%, 4.6% and 2.3%, respectively. Bland–Altman analysis showed good agreement between repeated measurements both for inter-observer

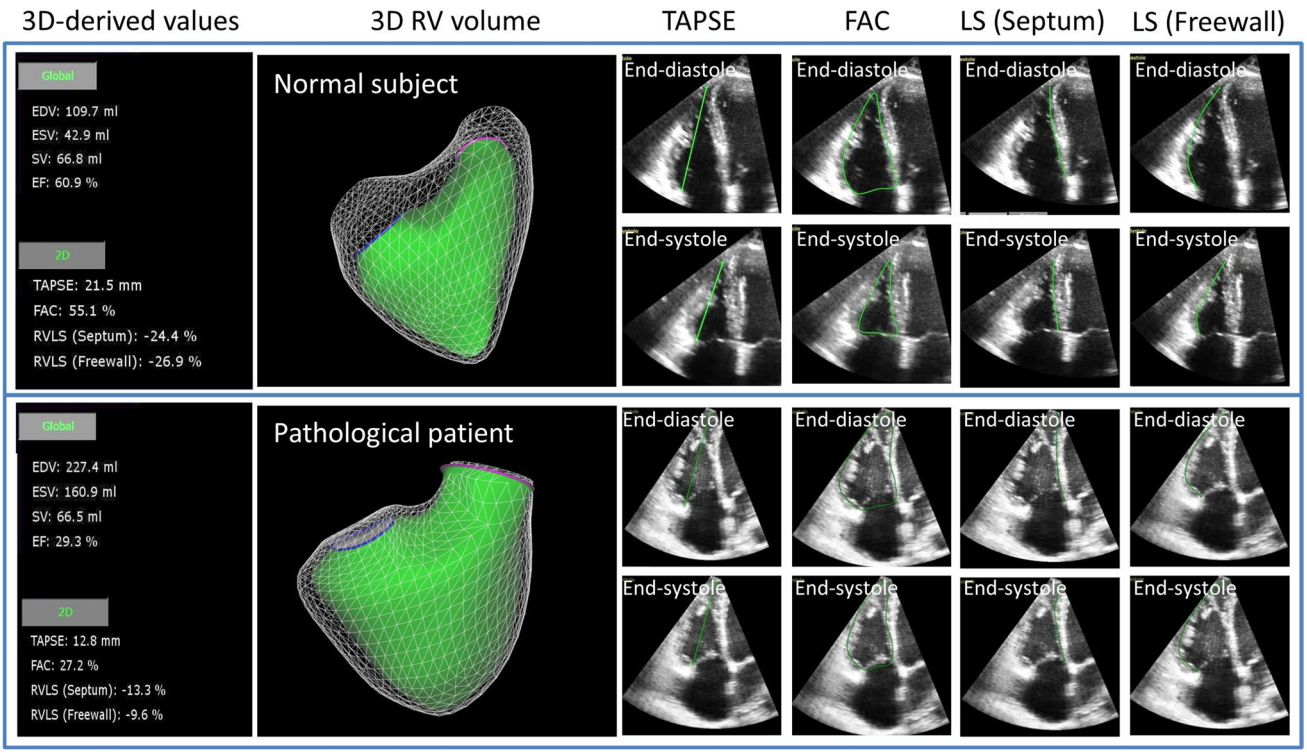

Fig. 2 Example of three-dimensional echocardiographic evaluation of right ventricular (RV) volumes and function in a normal subject (upper panels) and in a pathological patient (lower panels) with the on board dedicated software. RV reconstruction is computed along the cardiac cycle: end-diastolic (gray wireframe volume) and end-systolic (green solid volume) volumes, stroke volume and ejection fraction are depicted. Tricuspid annular plane systolic excursion (TAPSE), fractional area change (FAC), longitudinal strain (LS%) on septal and RV free wall are automatically obtained

Table 1 Demographic and echocardiographic characteristics of study population

	Total	Normal subjects	Pathological patients
Patients (F/M)	133 (40/93)	35(10/25)	98 (30/68)
Age (years)	63 ± 17	52 ± 19	66 ± 15**
BSA (m^2)	1.87 ± 0.22	1.83 ± 0.2	1.88 ± 0.2
2DE LV EDV (mL)	117.6 ± 47.7	100.7 ± 28	125.9 ± 51**
2DE LV ESV (mL)	58 ± 41	39.6 ± 13	66.6 ± 45**
2DE LV EF (%)	54 ± 14	61.0 ± 6	51.3 ± 15**
2DE RV ED area (cm^2)	21.9 ± 6	20.0 ± 6	22.8 ± 6*
2DE RV ES area (cm^2)	12.0 ± 5	9.5 ± 2	13.2 ± 5**
2DE FAC (%)	45.9 ± 10	51.7 ± 8	43.4 ± 10**
2DE TAPSE (mm)	20.8 ± 5.7	24.4 ± 4	19.4 ± 6**
PSV (cm/s)	12 ± 3	14.2 ± 2	11.3 ± 3**
RV MPI	0.42 ± 0.21	0.32 ± 0.1	0.46 ± 0.2**
RV dP/dt	607 ± 253	731 ± 199	555 ± 255**
SPP (mmHg)	36 ± 13	26.7 ± 4	39.2 ± 14**
2DE 3-segment LS (%)	− 24.4 ± 6	− 27.4 ± 4	− 23.2 ± 6**
2DE 6-segment LS (%)	− 19.8 ± 4	− 22.5 ± 3	− 18.8 ± 4**
3DE EDV (mL)	119.7 ± 41	106.0 ± 32	124.6 ± 43*
3DE ESV (mL)	59.2 ± 28	46.3 ± 17	63.8 ± 30**
3DE ejection fraction (%)	51.9 ± 9	57.1 ± 5	49.7 ± 10**
3DE FAC (%)	46.8 ± 11	52.4 ± 8	44.8 ± 11**
3DE TAPSE (mm)	17.6 ± 5	19.1 ± 3	17.0 ± 5*
3DE 3-segment LS (%)	− 24.6 ± 7	− 29.4 ± 5	− 22.9 ± 7**
3DE 6-segment LS (%)	− 19.2 ± 6	− 22.3 ± 4	− 18.1 ± 6**

2DE 2-dimensional echocardiography; *3DE* 3-dimensional echocardiography; *LV* left ventricular; *RV* right ventricular; *EDV* end diastolic volume; *ESV* end systolic volume; *EF* ejection fraction; *Ed* end diastolic; *ES* end systolic; *FAC* fractional area change; *TAPSE* tricuspid annular plane systolic excursion; *PSV* tissue Doppler peak systolic velocity; *MPI* myocardial performance index; *LS* longitudinal strain

*Significant difference $p < 0.05$ versus normal subjects

**Significant difference $p < 0.01$ versus normal subjects

variability (EDV: r^2 0.979, bias − 0.5 mL, LOA ± 9.9 mL; ESV r^2 0,976, bias − 0.5 mL, LOA ± 6.5 mL; EF r^2 0.903, bias 0.5%, LOA ± 5.3%) and for intra-observer variability (EDV: r^2 0.971, bias 1.5 mL, LOA ± 12 mL; ESV $r^2 = 0{,}965$, bias 1.3 mL, LOA ± 8.6 mL; EF r^2 0.792, bias 0.1%, LOA ± 7.9%).

Discussion

The main findings of our study in a consecutive series of patients referred for a standard transthoracic echocardiography including a comprehensive evaluation of the RV are: (a) this new on-board simplified software for 3DE RV reconstruction is highly feasible in the large majority of patients; (b) it reduces the time to obtain 3DE RV volume and RV EF; (c) it allows a comparable estimation of 3DE derived FAC and strain in comparison with 2DE traditional measurements, while TAPSE has a suboptimal correlation with the M-mode method, that may be easily manually corrected.

First of all the new simplified software for 3DE RV reconstruction is feasible and accurate in most of the patients and, being implemented on the echocardiographic machine, reduces significantly the time necessary to obtain 3DE RV volume and ejection fraction in the daily practice. We compared the results of the new on board analysis with the equivalent data computed with the off line system and the use of the new system significantly reduced the average time per patient. Not only the method allows a rapid (97 s vs. 209 s) and on-board analysis but it avoids RV data set loading and calculations on the off-line system. This outcome is very important in a busy laboratory and facilitates the introduction of a routine 3DE evaluation of the RV (in addition to the standard 2DE-Doppler protocol), or alternatively it may be utilized in selected cases.

No significant differences were observed between the two 3DE reconstruction modalities, with substantial time sparing in OB analysis. A comparison of 3DE volumetric data with CMR was performed in 22 cases and our data confirms the slight systematic underestimation of RV volumes by 3DE in comparison with CMR while RV EF is very similar with

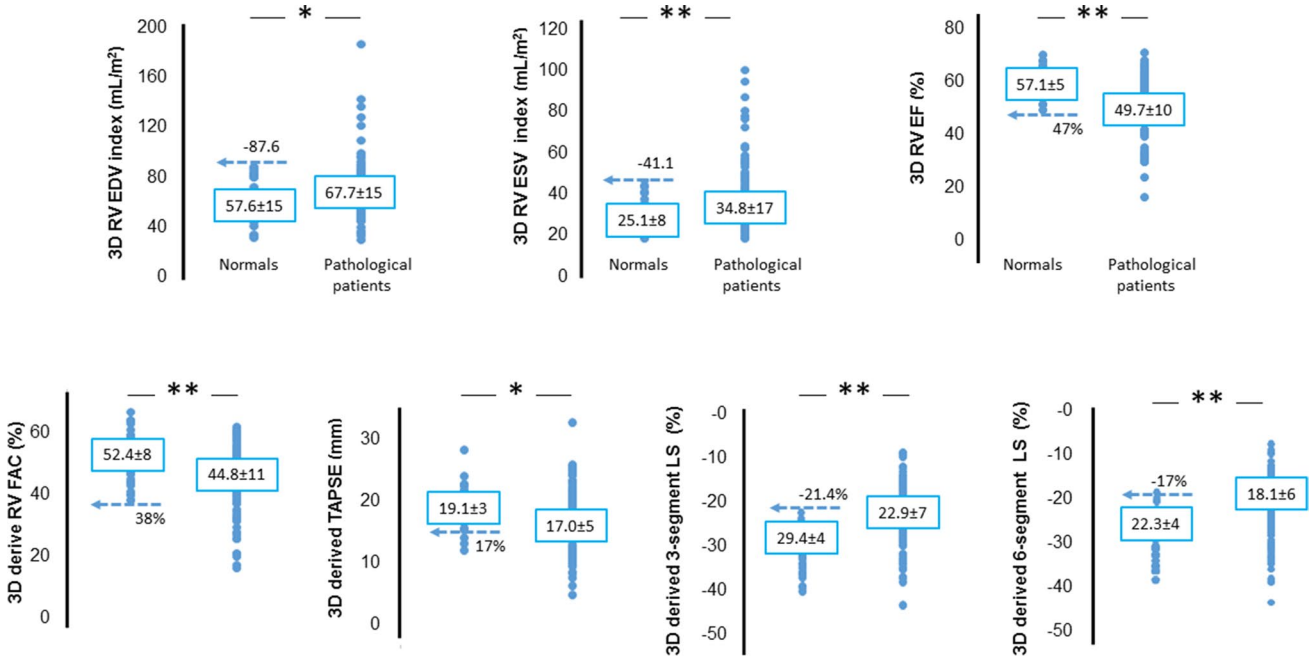

Fig. 3 Distribution of individual and mean values of right ventricular (RV) end-diastolic (EDV), end systolic (ESV) volumes, ejection fraction (EF), fractional area change (FAC), tricuspid annular plane systolic excursion (TAPSE), three-dimensional echocardiographic derived longitudinal strain (LS) on 3 and 6 segments in normal subjects and in patients. Arrows show the mean normal values minus 2 SD which represent the lower value of normality for these parameters in our population

Table 2 Comparison between (a) three-dimensional echocardiographic (3DE) derived right ventricular parameters evaluated with on board (OB 3DE) and off line (OFL 3DE) methods and (b) echocardiographic functional right ventricular parameters obtained from two- and three-dimensional echocardiographic images

(a) Three-dimensional echocardiographic (3DE) derived right ventricular parameters evaluated with on board (OB 3DE) and off line (OFL 3DE) methods	OB 3DE	OFL 3DE
3DE EDV index (mL/m^2)	64.2 ± 22	64 ± 21
3DE ESV index (mL/m^2)	31.7 ± 15	31.6 ± 15
3DE ejection fraction (%)	60 ± 21	61 ± 20
(b) Echocardiographic functional right ventricular parameters obtained from two- and three-dimensional echocardiographic images	OB 3DE	2DE
3DE FAC (%)	47 ± 11	46 ± 11
3DE TAPSE (mm)	17.6 ± 5	21 ± 6*
3DE 3-segment LS (%)	− 24.6 ± 7	− 24 ± 6
3DE 6-segment LS (%)	− 19.2 ± 6	− 20 ± 4

TAPSE tricuspid annular plane systolic excursion (mm); *LS* longitudinal strain; *EDV* end diastolic volume; *ESV* end systolic volume; *FAC* fractional area change (%)

*Significant difference $p < 0.05$ between three-dimensional and two dimensional measurement

the two methods [5, 9] and Bland Altman analysis showed similar differences in the comparison between CMR and OB and OFL respectively. RV volume and RVEF 3D echocardiographic underestimation v.s. CMR has been largely demonstrated and our results are similar to the data reported in previous works which utilized the traditional off-line software [20, 21].

Another important result is the accuracy of FAC and LS 3DE derived data in comparison with 2DE traditional measurements. The implementation of a multi-parameter RV evaluation has been demonstrated to improve diagnostic specificity and prognostic capacity in many RV pathologies [18, 19]. Moreover it adds relevant data in the selection of patients candidate to left ventricular assistance [23] and in the diagnosis and prognosis of arrhythmogenic dysplasia

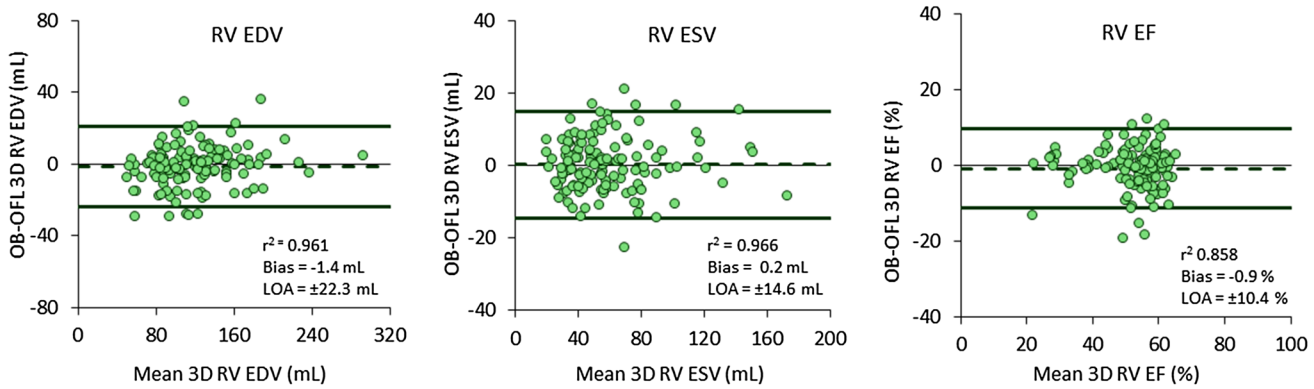

Fig. 4 Results of linear regression (top) and Bland–Altman analysis (bottom) for intra-observer measurements of right ventricular (RV) end diastolic volume (EDV), end-systolic volume (ESV) and ejection fraction (EF) obtained from three-dimensional echocardiographic images off line (OFL) and on board (OB). The dashed lines represent bias and the solid lines ± 1.96 standard deviations. *LOA* limits of agreement

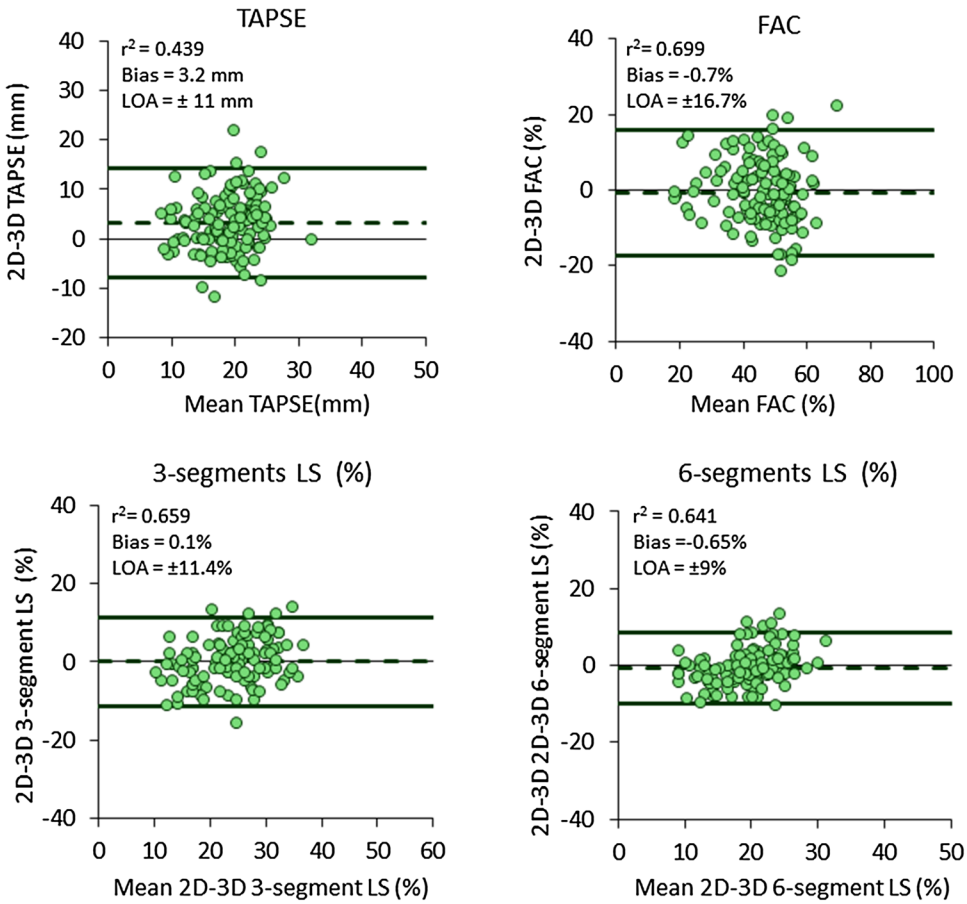

Fig. 5 Results of linear regression (top) and Bland–Altman analysis (bottom) for Tricuspid annular plane systolic excursion (TAPSE), Fractional area change (FAC), Longitudinal strain (LS) on 3 and 6 segments, obtained from two- and three-dimensional echocardiographic images. The dashed lines represent bias and the solid lines ± 1.96 standard deviations. *LOA* limits of agreement

[2] and pulmonary hypertension [1, 18]. It has also been proved recently that RV strain is an important diagnostic parameter, less load dependent in most of the clinical settings involving RV [16, 17]. Our results show a higher accuracy of free wall strain (3 segment model) in comparison with the 6 segment method which include septal deformation values, in identifying normal patients. In fact 2 normal subjects have a 3D derived pathological 6 segment strain, with normal 3-segment LS in the absence of RV dysfunction. However no significant difference between 2DE and 3DE both 3- and 6-segment data were observed with a trivial systematic under estimation of the 3DE values. This result

Table 3 Correlations between three-dimensional echocardiographic (3DE) derived and traditional two-dimensional echocardiographic (2DE) and Doppler right ventricular (RV) functional parameter in the all population

	SPP r	PSV r	dP/dt r	MPI r
3DE RV EF	−0.427**	0.424**	0.395**	−0. 324**
3DE FSA	−0.381**	0.425**	0.449**	−0.237**
3DE TAPSE	−0.142 ns	0.404	0.204 ns	−0.267**
3DE 3-segment LS	−0.355**	0.542**	0.405**	−0.292**
3DE 6-segment LS	−0.311**	0.490**	0.424**	−0.313**

EF ejection fraction; *FAC* fractional area change; *TAPSE* tricuspid annular plane systolic velocity; *MPI* myocardial performance index; *LS* longitudinal strain; *SPP* systolic pulmonary pressure; *PSV* peak systolic excursion

**Significant difference $p < 0.001$ versus normal subjects

is in agreement with similar data concerning the comparison of left ventricular 3DE and 2DE longitudinal strain and referred to the lower spatial and temporal resolution of 3DE which produces smoother results avoiding sharp peaks [24, 25]. Therefore this on board 3DE software further facilitates the complete assessment of RV FAC and strain and of RV volumes and ejection fraction.

3DE derived TAPSE has a suboptimal correlation with the traditional 2DE value, and is not correlated with the traditional RV performance parameters. Specifically by using a traditional 17 mm cut-off for normality [10, 26], 3D derived TAPSE has poor validity in identifying normal subjects and mean value of 3DE derived TAPSE in normals (19.1 ± 3 mm) was lower in comparison with M-Mode 2DE guided traditional measurement (24.4 ± 4 mm, $p < 0.001$). TAPSE is known to represent RV ventricular longitudinal function which is derived from the measure of tricuspid annular systolic movement with M-mode aligned to the tricuspid annulus. Proper alignment of M-mode cursor with the direction of RV longitudinal excursion should be achieved from the apical approach in an ideal apical approach while probably 3DE derived TAPSE suffers from the 3DE volume acquisition view that is slightly oriented to the RV, therefore interfering with the correct alignment. However despite this limitation, the system allows an easy correction of the M-mode line to obtain the proper alignment.

Limitation of the study

The present study has some limitations, first of all the incorporation of consecutive patients with normal subjects and with different heart pathologies allowed the enrollment of a large sample size, however the number of subjects with a certain abnormal RV is small (26 subjects). A prospective study with a selected population of patients with RV pressure or volume overload would reinforce our data.

A second limitation is the relative low number of patients included, in our population (140 subject). However, as reported in "Statistical analysis" section, the sample size was sufficient to allow a correct evaluation and comparison between OB and OFL methods.

Despite the small number of subjects (22 patients) with CMR due to the limited clinical indication to CMR in our series of patients, validation of 3DE RV measurements v.s. CMR has extensively been demonstrated in previous works [5, 9, 20] and was not the aim of our current study.

Table 4 Comparison of the accuracy of RV measurements by OB 3DE and by OFL 3DE versus CMR (22 patients)

	OB 3DE	CMR	Correlation	Bias	LOA
Correlations between OB 3DE and CMR					
RV EDV (mL)	132.9 ± 51	152.4 ± 52	0.922	− 21.5	41.3
RV ESV (mL)	63.4 ± 30	71.6 ± 33	0.929	− 8.2	24.8
RV EF (%)	53.6 ± 9	55.1 ± 10	0.745	− 1.2	14.8
	OFL 3DE	CMR	Correlation	Bias	LOA
Correlations between OFL 3DE and CMR					
RV EDV (mL)	130.1 ± 52	152.4 ± 52	0.903	− 22.1	45.1
RV ESV (mL)	60.9 ± 30	71.6 ± 33	0.928	− 9.9	24.9
RV EF (%)	54.1 ± 9	55.1 ± 10	0.776	− 1	13.7

RV right ventricular; *OB* on board; *OFL* off line; *3DE* three dimensional echocardiographic; *CMR* cardiac magnetic resonance; *EDV* end diastolic volume; *ESV* end systolic volume; *EF* ejection fraction; *LOA* limits of agreement

Conclusions

Echocardiographic assessment of the RV is difficult because of its complex shape. Right ventricular performance is known to be a major determinant of clinical status and long-term outcomes in patients with heart failure, pulmonary hypertension, cardiomyopathies, and congenital heart disease [1–7]. In this regard CMR imaging is considered the reference for RV volume and ejection fraction, but it has several logistic limitations including costs, availability and contraindications.

Current echocardiographic guidelines [10, 16] recommend the assessment of RV function by surrogate indices that represent RV longitudinal function, including M-mode measurements of tricuspid annular plane systolic excursion and Doppler tissue imaging measurements of peak systolic velocity. Recently the introduction of 3DE echocardiographic imaging allows direct measurements of RV volume without relying on geometric assumptions and in this study we demonstrated that 3DE volumes, EF and other traditional RV parameters may be easily obtained in a very short time thus allowing a comprehensive RV evaluation inside the standard transthoracic protocol. By a single 3DE acquisition from the apical view in approximately 74 s, volumes and systolic function (either EF and longitudinal and strain values) may be calculated. Since a comprehensive RV evaluation include hemodynamic and morphofunctional data, the standard transthoracic approach (with all LV and left atrial parameters, and LV non-invasive hemodynamics) may further be completed by this simple method and right side hemodynamic parameters (SPP, inferior vena cava collapsibility).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Research involving human participants This article does not contain any studies with animals performed by any of the authors.

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