Archives of Cardiovascular Disease (2015) 108, 5—15

ELSEVIER MASSON

Available online at ScienceDirect www.sciencedirect.com

Elsevier Masson France EM|consulte www.em-consulte.com/en

CLINICAL RESEARCH

Multivariable assessment of the right ventricle by echocardiography in patients with repaired tetralogy of Fallot undergoing pulmonary valve replacement: A comparative study with magnetic resonance imaging

Évaluation multiparamétrique du ventricule droit par échocardiographie chez les patients avec une tétralogie de Fallot ayant bénéficié d'une chirurgie de remplacement valvulaire pulmonaire : étude comparative à l'IRM

Jean-Bernard Selly[a,*], **Xavier Iriart**[a], **François Roubertie**[a], **Philippe Mauriat**[a], **Jan Marek**[b], **Emmanuelle Guilhon**[a], **Karim Jamal-Bey**[c], **Jean-Benoît Thambo**[a]

[a] *Division of Congenital Heart Disease, Bordeaux Hospital University Center, avenue de Magellan, 33604 Bordeaux, France*
[b] *Great Ormond Street Hospital for Children, London, United Kingdom*
[c] *Division of Pediatrics, Reunion Hospital University Center, Saint-Pierre, Reunion*

Received 22 December 2013; received in revised form 17 July 2014; accepted 23 July 2014
Available online 12 November 2014

Abbreviations: 3D, three-dimensional; AUC, area under the receiver operating characteristic curve; FAC, fractional area change; LV, left ventricle; MPI, myocardial performance index; MRI, magnetic resonance imaging; PVR, pulmonary valve replacement; ROC, receiver operating characteristic; RT3DE, real-time three-dimensional echocardiography; RVEDV, right ventricular end-diastolic volume; RVEF, right ventricular ejection fraction; RVESV, right ventricular end-systolic volume; rTOF, repaired tetralogy of Fallot; RV, right ventricle/ventricular; RVOT, right ventricular outflow tract; TAPSE, tricuspid annular plane systolic excursion; TAPSV, tricuspid annular peak systolic velocity; TOF, tetralogy of Fallot.

* Corresponding author.
E-mail address: bernardselly@hotmail.com (J.-B. Selly).

http://dx.doi.org/10.1016/j.acvd.2014.07.054
1875-2136/

KEYWORDS
Tetralogy of Fallot;
Echocardiography;
Magnetic resonance imaging;
Pulmonary valve replacement;
Right ventricle

Summary
Background. — Evaluation of the right ventricle (RV) using transthoracic echocardiography is challenging in patients with repaired tetralogy of Fallot (rTOF).
Aims. — To evaluate the accuracy of conventional echocardiographic variables and real-time three-dimensional echocardiography (RT3DE) in assessing right ventricular (RV) volumes and function compared with magnetic resonance imaging (MRI), in adult patients with rTOF and referred for pulmonary valve replacement (PVR).
Methods. — Complete echocardiography was performed on 26 consecutive patients referred for PVR, before and 1 year after surgery. All variables were compared with MRI.
Results. — Correlations between conventional variables and MRI were absent or poor when assessing RV ejection fraction (RVEF), except for fractional area of change (FAC; $r = 0.70$, $P < 0.01$ before PVR; $r = 0.68$, $P < 0.01$ after PVR) and RT3DE ($r = 0.96$, $P < 0.01$ before PVR; $r = 0.98$, $P < 0.01$ after PVR). The RV volume correlation between RT3DE and MRI was excellent before and after surgery for RV end-diastolic volume ($r = 0.88$, $P < 0.01$ and $r = 0.91$, $P < 0.01$, respectively) and RV end-systolic volume ($r = 0.92$, $P < 0.01$ and $r = 0.95$, $P < 0.01$, respectively). The accuracy of these indices, as a diagnostic test for impaired RV (<45%), was good: Youden's indexes varied from 0.47 to 0.89; areas under the receiver operating characteristic curve before and after PVR were 0.86 and 0.81 for FAC and 0.98 and 0.97 for RT3DE, respectively.
Conclusion. — Commonly used echocardiography variables, such as tricuspid annular plane systolic excursion and tricuspid annular peak systolic velocity, did not sensitively evaluate global RVEF. A global approach, that includes the whole RV and integration of its different components, was more reliable in patients with rTOF.

MOTS CLÉS
Tétralogie de Fallot ;
Échocardiographie ;
IRM ;
Remplacement valvulaire pulmonaire ;
Ventricule droit

Résumé
Contexte. — L'évaluation du ventricule droit (VD) par l'échocardiographie trans-thoracique est un véritable défi chez les patients avec une tétralogie de Fallot corrigée.
Objectifs. — Nous avons ainsi évalué la précision des paramètres échographiques conventionnels et ceux de l'échocardiographie en 3D pour analyser les volumes et la fonction du VD en comparaison à l'évaluation par IRM, chez les patients adultes avec tétralogie de Fallot corrigée adressés pour une chirurgie de remplacement valvulaire pulmonaire (RVP).
Méthodes. — Une échocardiographie complète a été réalisée chez 26 patients adressés pour RVP, avant chirurgie et un an après chirurgie. Les paramètres obtenus ont été comparés à ceux issus de l'IRM.
Résultats. — La corrélation entre les paramètres conventionnels et l'IRM était absente ou faible en termes d'analyse de la fonction du VD excepté pour la fraction de raccourcissement de surface FRS ($r = 0{,}70$, $p < 0{,}01$ et $r = 0{,}68$, $p < 0{,}01$, avant et après RVP, respectivement) et l'échocardiographie 3D ($r = 0{,}96$, $p < 0{,}01$ et $r = 0{,}98$, $p < 0{,}01$ avant et après RVP, respectivement). La corrélation des volumes ventriculaires entre l'échocardiographie 3D et l'IRM était excellente avant et après RVP pour le volume télé-diastolique du VD ($r = 0{,}88$, $p < 0{,}01$ et $r = 0{,}91$, $p < 0{,}01$, respectivement), et pour le volume télé-systolique ($r = 0{,}92$, $p < 0{,}01$ et $r = 0{,}95$, $p < 0{,}01$, respectivement). La précision de ces mêmes indices en tant que test diagnostique de l'altération de la fonction VD (< 45 %) était bonne : les indices de Youden variaient de 0,47 à 0,89 et les aires sous la courbe de 0,86 et 0,81 pour la FRS, 0,98 et 0,97 pour l'échocardiographie 3D, respectivement avant et après RVP.
Conclusion. — Les paramètres échocardiographiques habituellement utilisés, comme le TAPSE et le S'VD, ne sont pas sensibles à évaluer la fonction du VD. Une approche globale, qui prend en compte l'ensemble du VD et l'intégration de ses différents composants, est plus adaptée chez les patients avec tétralogie de Fallot corrigée.

Introduction

Tetralogy of Fallot (TOF) is the most common cause of cyanotic congenital heart disease, and is associated with a high prevalence of pulmonary regurgitation following repair, which often requires later pulmonary valve replacement (PVR) [1]. Monitoring right ventricular (RV) volume and function is mandatory when managing these patients.

Echocardiography is the most widely available and cost-effective imaging modality, but its use in assessing the right ventricle (RV) after repaired TOF (rTOF) remains challenging. American and European guidelines [2] for chamber quantification recommend the use of different variables to assess RV function, such as tricuspid annular plane systolic excursion (TAPSE) and tricuspid annular peak systolic velocity (TAPSV) using tissue Doppler imaging, myocardial performance index (MPI) and fractional area of change (FAC). These variables have been validated in patients with coronary artery disease and cardiomyopathy. Other advanced variables, such as real-time three-dimensional echocardiography (RT3DE), are promising in assessing RV function [2]. The normal RV contraction pattern is different from that of the left ventricle (LV) because of different muscle fibre organization and low vascular bed impedance [3]. Longitudinal shortening is the main component of RV systolic function, and measurement of simple variables, such as TAPSE or TAPSV, has enabled assessment of RV function in a simple, repeatable and reproducible way in normal subjects and in patients with ischaemic heart disease [4,5]. However, there are few data on the reliability of these conventional or advanced variables in patients with rTOF associated with a severely dilated RV related to chronic pulmonary regurgitation.

The objective of this study was to evaluate the accuracy of echocardiographic variables, including conventional variables (TAPSE, MPI, FAC, TAPSV) and RT3DE, to assess RV volume and function compared with magnetic resonance imaging (MRI), in patients with rTOF referred for PVR, as MRI is widely accepted as the gold standard for RV assessment in patients with congenital heart disease [6]. Patients were re-evaluated 1 year after surgery to determine the effects of surgery and any change to these variables.

Methods

Subjects

We enrolled 26 consecutive patients referred for PVR between 2010 and 2011 in the Adult Congenital Heart Disease Clinic at the University Hospital of Bordeaux. All patients were evaluated before and 1 year after surgery. Our institutional review board approved the study and all subjects gave their informed consent. Transthoracic echocardiography and MRI at rest were performed on the same day or on a subsequent day, according to the following protocols.

Echocardiography

Standard echocardiography

Transthoracic echocardiography was performed using Vivid 7® (GE Vingmed Ultrasound A.S., Horten, Norway) by two experienced cardiologists (J.-B.S. and X.I.). All echocardiographic recordings were stored digitally for offline analysis. Measurements were made in three cardiac cycles, and average values were used for statistical analyses.

TAPSE was assessed in M-mode in the apical four-chamber view, and RV end-diastolic and end-systolic areas were assessed in the same view. From these measurements, we calculated the FAC. TAPSV at the junction of the RV free wall and the tricuspid annulus was assessed using pulsed tissue Doppler echocardiography. The RV MPI — defined as (isovolumic contraction + isovolumic relaxation time)/ejection time — was also assessed by Doppler echocardiography.

Three-dimensional echocardiography

Data acquisition

Three-dimensional echocardiography was performed using a 3 V matrix-array transducer (1—4 MHz). The entire echocardiography dataset was acquired from a single apical transducer location that was slightly modified from the traditional apical four-chamber view: the right-sided structures were maximized and clearly visualized, and appeared in the centre of the field of view. Data acquisition required electrocardiogram gating, so output was not truly in real-time, but was actually reconstructed from four subvolumes. The entire reconstructed three-dimensional (3D) dataset was first inspected for whole-body motion artefacts that might have occurred during data acquisition. The reconstructed data were then reviewed as a loop with a temporal resolution of 55—65 ms (15—18 vol/s).

Automated border detection and volume-computation algorithm

Analyses of original raw data were performed using dedicated RV analysis software (TomTec Imaging Systems GmbH, Munich, Germany) using the usual protocol for this software, as described in our previous study [7]. The 3D dataset could be manipulated offline by a series of translational, rotational and pivoting manoeuvres to best visualize RV inflow and outflow tracts, and to display the reference planes. End-diastolic and end-systolic phases were first defined, then contours were manually drawn in end-diastolic and end-systolic images for three selected images (four-chamber, coronal and sagittal views) and adjusted as closely as possible to the endocardial border (Fig. 1). Heavy parietal trabeculations were included in the RV chamber, as performed using MRI. These contours served to initiate the semiautomatic algorithm. Using this method and blinded to the MRI results, the software analysed RV volumes and function.

Magnetic resonance imaging

MRI was performed on a 1.5 T system (Sonata; Siemens, Erlangen, Germany) with a phased-array radiofrequency receiver coil placed on the chest. All images were gated to the electrocardiogram. Double oblique long-axis and four-chamber scouts were acquired to obtain a true short-axis reference. Steady-state free-precession prospectively electrocardiogram-gated breath-hold images, encompassing the whole RV, were then acquired in the short-axis orientation, with no gaps between the slices (TrueFISP sequence: slice thickness, 7 mm; TE, 1.53 ms; TR, 33.6 ms [depending on the R—R interval]; matrix, 256 × 256 mm; field of view, 38 cm). RV end-systolic volume (RVESV), RV end-diastolic volume (RVEDV) and RV ejection fraction (RVEF) were measured on a postprocessing workstation (Leonardo; Siemens), using commercially available software (Syngo Argus; Siemens), by a radiologist blinded to the results of the echocardiography (Fig. 2).

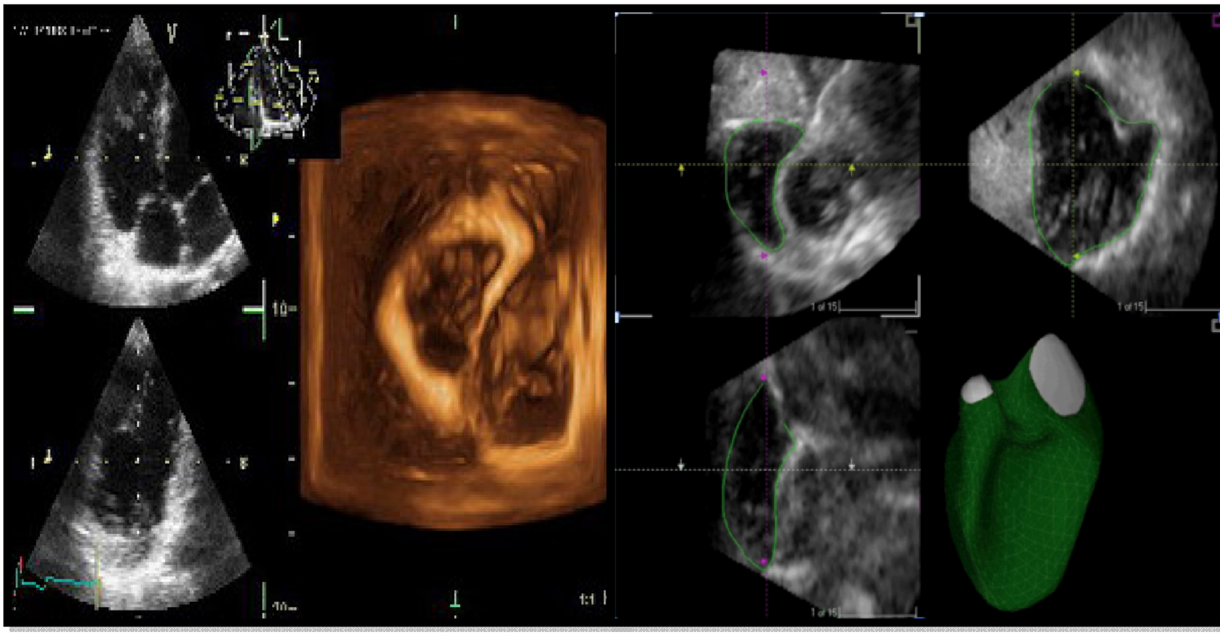

Figure 1. Right ventricle assessment by three-dimensional echocardiography.

Statistical analyses

Relationships between the echocardiographic variables of RV function and MRI of RVEF were evaluated using Pearson's correlation coefficient and linear regression. The same method was used to compare the RV volumes obtained by RT3DE with MRI RV volumes. To estimate echocardiographic semi-quantitative impaired RV systolic function, the data were presented as means ± standard deviations. Stratified correlation, according to whether MRI RVEF was normal or not, was done, and a Fisher's z-transformation was used to compare the correlations. A threshold value of 45% for MRI RVEF was chosen according to the reference radionucleotide and the MRI results described in the review of RV function by Haddad et al. [8]. A *P*-value <0.05 was considered statistically significant. Statistical analyses were performed using SAS software (version 9.1; SAS Institute, Cary, NC, USA) and receiver operating characteristic (ROC) curve analyses were obtained using R (version 2.15.2; R Foundation for Statistical Computing, Vienna, Austria).

Results

Study population

Twenty-six patients with rTOF were included in this study. All patients underwent surgical PVR for severe pulmonary regurgitation, defined as MRI pulmonary regurgitation fraction >40% and peak velocity across the RV outflow tract (RVOT) <2.5 m/s. The patients' characteristics are presented in Table 1: their mean age was 27 ± 12 years.

Magnetic resonance imaging results

The MRI results are shown in Table 2. In our study, 17 (65%) patients had an RVEDV of >150 mL/m^2. One year after PVR, RVEDV had decreased significantly from 152.1 ± 38.5 to 111.7 ± 31.7 mL/m^2 ($P < 0.01$) and RVESV had decreased from 91.6 ± 32.5 to 66.2 ± 27.6 mL/m^2 ($P < 0.01$). There was no significant change in RVEF when measured by MRI.

Echocardiographic results

All patients had echocardiography before PVR and 1 year after surgery. The overall results and the numbers of

Table 1 Patients' characteristics.

Age (years), mean ± S.D.	27 ± 12
Ratio men: women, n/n	16/10
Palliative surgery, n	14
Complete repair (years), mean	4
Transannular patch, n	16
Delay between complete repair and PVR (years), mean	24
NYHA classification, n	
I	9
II	10
III	6
IV	1
PVR indication, n	
Severe PR, RVEDV >150 mL/m^2, symptomatic	14
Severe PR, RVEDV <150 mL/m^2, symptomatic	6
Severe PR, RVEDV >150 mL/m^2, asymptomatic	6

NYHA: New York Heart Association; PVR: pulmonary valve replacement; PR: pulmonary regurgitation; RVEDV: right ventricular end-diastolic volume.

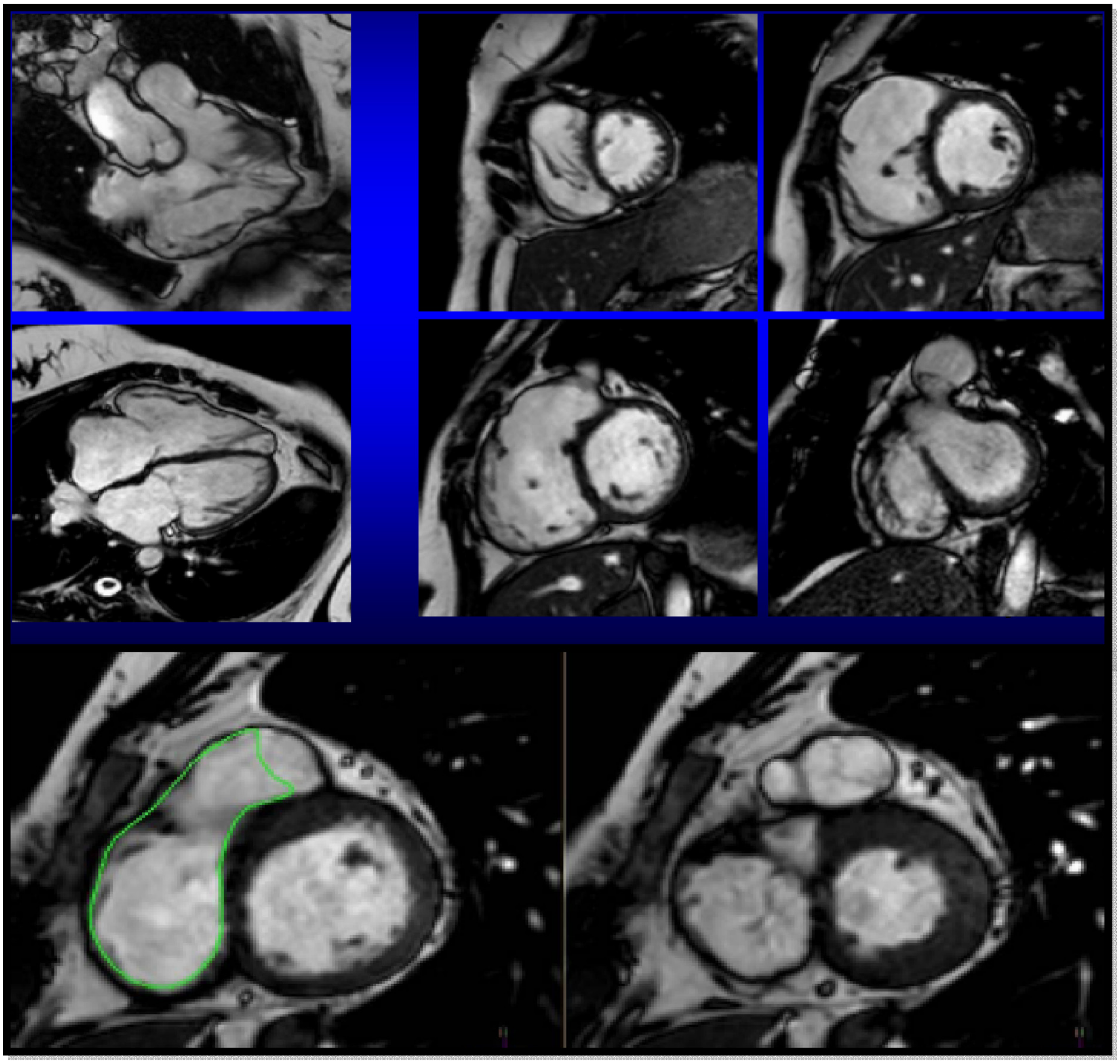

Figure 2. Right ventricle assessment by magnetic resonance imaging.

patients in whom respective variables were assessed are shown in Table 3. Assessment of standard variables was feasible for most patients. Assessment was more difficult for RT3DE variables before PVR because of the larger RV volumes. The feasibility of RT3DE was 46% before surgery and 57% 1 year after surgery.

Table 2 Magnetic resonance imaging results ($n = 26$).

MRI variable	Before surgery	After surgery	P[a]
RVEDV (mL/m^2)	152.1 ± 38.5	111.7 ± 31.7	<0.01
RVESV (mL/m^2)	91.6 ± 32.5	66.2 ± 27.6	<0.01
RVEF (%)	41.1 ± 12.5	44.4 ± 10.3	0.30

Data are mean ± standard deviation. MRI: magnetic resonance imaging; RVEDV: right ventricular end-diastolic volume; RVEF: right ventricular ejection fraction; RVESV: right ventricular end-systolic volume.
[a] Student's.

One year after PVR, RVEDV had decreased significantly from 94.9 ± 23.9 to 67.4 ± 20.1 mL/m^2 ($P < 0.01$) and RVESV had decreased from 57.4 ± 18.9 to 39.4 ± 20.3 mL/m^2 ($P < 0.01$) based on RT3DE analysis. There was no significant change in RVEF when assessed by RT3DE.

Agreement between echocardiographic variables and right ventricular ejection fraction by magnetic resonance imaging

Table 4 shows the correlations between echocardiographic variables of RV function and RVEF assessed by MRI before and 1 year after surgery. The commonly used variables, such as TAPSE, TAPSV and MPI, did not correlate significantly with MRI RVEF assessment. In contrast, FAC and RT3DE were highly correlated with MRI, both before and after surgery (FAC: $r = 0.70$, $P < 0.01$ preoperatively and $r = 0.68$, $P < 0.01$ postoperatively; RT3DE: $r = 0.96$, $P < 0.01$ preoperatively and $r = 0.98$, $P < 0.01$ postoperatively). Bland-Altman

Table 3 Echocardiographic results ($n=26$).

Echocardiography variable	Before surgery		After surgery		P[a]
	Mean ± S.D.	n[b]	Mean ± S.D.	n[b]	
TAPSE (mm)	17.2 ± 2.9	26	16.2 ± 2.9	26	NS
TAPSV (cm/s)	9.7 ± 2.3	26	8.9 ± 1.7	26	NS
MPI	0.35 ± 0.21	24	0.38 ± 0.14	24	NS
FAC (%)	45.9 ± 10.9	24	38.8 ± 11.1	26	0.06
RVEDV (mL/m^2)	94.9 ± 23.9	12 (46%)	67.4 ± 20.1	15 (57%)	0.01
RVESV (mL/m^2)	57.4 ± 18.9	12	39.4 ± 20.3	15	0.03
RVEF by RT3DE (%)	40.2 ± 10.3	12	44.1 ± 11.4	15	0.39

FAC: fractional area of change; MPI: myocardial performance index; NS: not significant; RT3DE: real-time three-dimensional echocardiography; RVEDV: right ventricular end-diastolic volume; RVEF: right ventricular ejection fraction; RVESV: right ventricular end-systolic volume; S.D.: standard deviation; TAPSE: tricuspid annular plane systolic excursion; TAPSV: tricuspid annular peak systolic velocity.
[a] Student's.
[b] Number of patients in whom the variable was assessed.

curves confirmed the accuracy of FAC and RT3DE in assessing RVEF compared with MRI before and after PVR: the mean bias was 0.2 ± 4.4 before PVR and −0.4 ± 4.3 after PVR for RT3DE, and −2.9 ± 22.1 before PVR and 3 ± 20.9 after PVR for FAC (Fig. 3).

Agreement between echocardiographic variables for estimation of impaired right ventricular function

We also aimed to determine which variables provided a reliable estimation of impaired RV systolic function. In accordance with the lower range of RV normal function of 45% [8], the echocardiographic variables were analysed before and after surgery using this threshold, based on the MRI RVEF measurement.

Results in Table 5 show that FAC could significantly determine impaired RV systolic function, before and after surgery. TAPSE, tissue Doppler imaging and MPI were not relevant in estimating impaired RV function.

By tracing the ROC curves, the best FAC thresholds for determining impaired RV function were 44.5% before PVR (area under the ROC curve [AUC] = 0.86; Se = 0.86; Sp = 0.67; Youden's index = 0.53) and 36.8% after PVR (AUC = 0.81; Se = 0.74; Sp = 0.73; Youden's index = 0.47). For RT3DE, the best thresholds were 41% before PVR (AUC = 0.98; Se = 1; Sp = 0.89; Youden's index = 0.89) and 48.5% after PVR (AUC = 0.97; Se = 0.89; Sp = 0.1; Youden's index = 0.89; Fig. 4).

Agreement between echocardiographic variables and right ventricular volumes assessed by magnetic resonance imaging

Table 6 and Fig. 5 show that the correlation for RV volume between RT3DE and MRI was excellent, both before and after surgery ($r=0.88$, $P<0.01$ and $r=0.91$, $P<0.01$, respectively, for RVEDV; $r=0.92$, $P<0.01$ and $r=0.95$, $P<0.01$, respectively, for RVESV). Correlation was even better postoperatively, as the volumes had decreased dramatically.

We found that RT3DE analysis was reproducible: the correlations between MRI and RT3DE (the volume variations for each individual before and after surgery) were excellent ($r=0.94$, $P<0.01$ for RVEDV; $r=0.93$, $P<0.01$ for RVESV).

Limitations

Despite an excellent correlation with MRI, the feasibility of RT3DE remains limited in severely dilated RVs, which is why

Table 4 Agreement between echocardiographic variables and measurement of right ventricular ejection fraction by magnetic resonance imaging.

Echocardiography variable	Before surgery: RVEF by MRI		After surgery: RVEF by MRI	
	r	P	r	P
TAPSE	0.11	0.64	0.17	0.38
TAPSV	0.08	0.72	0.39	0.06
MPI	0.07	0.82	0.27	0.24
FAC	0.70	<0.01	0.68	<0.01
RVEF by RT3DE	0.96	<0.01	0.98	<0.01

FAC: fractional area of change; RT3DE: real-time three-dimensional echocardiography; RVEDV: right ventricular end-diastolic volume; RVEF: right ventricular ejection fraction; RVESV: right ventricular end-systolic volume; TAPSE: tricuspid annulus-plane systolic excursion; TAPSV: tricuspid annulus-peak systolic velocity.

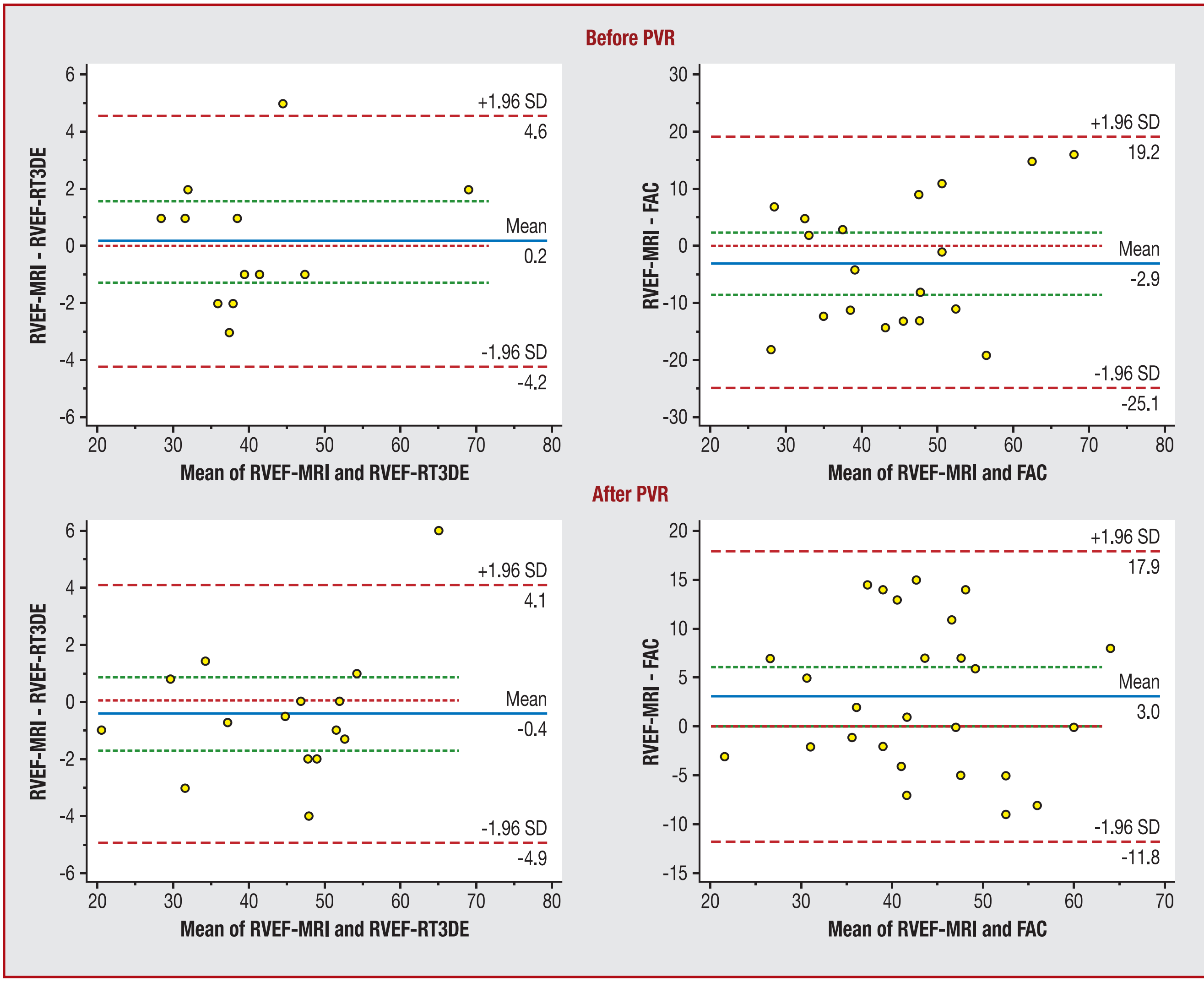

Figure 3. Bland-Altman plots depicting accuracy of fractional area of change (FAC) and real-time three-dimensional echocardiography (RT3DE) in assessing right ventricular ejection fraction (RVEF) compared with magnetic resonance imaging (MRI), before and after pulmonary valve replacement (PVR). SD: standard deviation.

RT3DE analysis was performed on 46% of the patients before surgery and on 57% after PVR.

We also need to underline the major underestimation of RV volumes by RT3DE compared with MRI. RVESV and RVEDV assessed by RT3DE were underestimated by around 41% before and after PVR compared with the assessment of RV volumes by MRI.

Discussion

In our study, longitudinal shortening variables focused on RV inflow (TAPSE, TAPSV) showed no significant correlation with global systolic RV function using MRI. Similar findings have been reported in recent studies in both adults and children with rTOF and chronic volume overload [9—11]. The most

Table 5 Echocardiographic variables and measurement of right ventricular ejection fraction with significant agreement with estimation of impaired right ventricular ejection fraction by magnetic resonance imaging.

Echocardiography variable	Before surgery		After surgery	
	RVEF MRI <45% (*n* = 19)	RVEF MRI >45% (*n* = 7)	RVEF MRI <45% (*n* = 11)	RVEF MRI >45% (*n* = 15)
FAC (%)	41.2 ± 9.5	54 ± 8.2	32 ± 7.3	43.3 ± 10.3
RVEF by RT3DE (%)	36.1 ± 4.9	52.7 ± 13.1	33.25 ± 8	51.1 ± 4.3

Data are mean ± standard deviation. FAC: fractional area of change; MRI: magnetic resonance imaging; RT3DE: real-time three-dimensional echocardiography; RVEF: right ventricular ejection fraction.

Table 6 Agreement between echocardiographic and magnetic resonance imaging right ventricular volume variables.

	RVEDV by MRI		RVESV by MRI	
	r	*P*	*r*	*P*
Before surgery				
RVEDV by RT3DE	0.88	<0.01	0.67	0.02
RVESV by RT3DE	0.80	<0.01	0.92	<0.01
After surgery				
RVEDV by RT3DE	0.91	<0.01	0.90	<0.01
RVESV by RT3DE	0.92	<0.01	0.95	<0.01

MRI: magnetic resonance imaging; RT3DE: real-time three-dimensional echocardiography; RVEDV: right ventricular end-diastolic volume; RVESV: right ventricular end-systolic volume.

likely reason for this is the altered regional contraction pattern in this population, which may be caused by altered muscle fibre orientation. Sanchez-Quintana et al. reported that TOF patients have a middle layer of circumferential fibres in their RVs that is not present in normal RVs [3]. Such a middle layer is normally present in the LV and contains circumferential fibres that are involved in radial shortening.

Furthermore, RV shape in patients with TOF differs from normal subjects in several ways [11]: patients with TOF have a larger normalized cross-sectional area and the RV has a rounder shape in its apical planes. Morcos et al. and Sheehan et al. have described the importance of apex remodelling and demonstrated that the apex is more important than the base in TOF patients with impaired RV function [10,11].

In addition, the interventricular septum undergoes relatively less enlargement. Also, patients with TOF have a bulging basal tricuspid valve. This basal bulging is amplified by tilting the tricuspid annulus, and could be an additional explanation for the lack of sensitivity of the commonly used TAPSE and TAPSV as markers for global RV function. In contrast, the use of variables that integrate both longitudinal and circumferential shortening, such as FAC or RT3DE, may improve evaluation of global RV systolic function.

FAC is known to have a good correlation with MRI RVEF in adult patients with acquired disease (Arnould et al. [12] reported $r = 0.68$ and $P < 0.01$; Leong et al. [13] reported $r = 0.71$ and $P < 0.01$). In our study, FAC was the only commonly used echocardiographic variable that was significantly correlated with RVEF estimated by MRI. Greutmann et al. [14] have shown that FAC was significantly lower in rTOF patients, with RVEF by MRI <35% compared with rTOF patients who had RVEF by MRI >50%. This is probably because of the integration of the different contraction patterns of the RV body analysed by FAC, which integrates longitudinal and radial components of contraction. Kutty et al. [15] recently demonstrated that regional dysfunction of the RVOT reduces the accuracy of TAPSV to evaluate global RV systolic function. Although several studies have examined the utility of TAPSV in TOF, these investigations did not address the potentially confounding effect of RVOT dysfunction on myocardial velocities at the base of the RV [9,11,15].

In patients with large akinetic or dyskinetic RVOT patches and/or scar tissue, measurements of tissue velocities at the base of the RV may not accurately reflect global RV systolic function. This may be because, in the normal heart, the function of the inflow and outflow components of the RV are closely related, whereas this relationship is weak and unpredictable in patients who have undergone rTOF. Consequently, in the presence of a dyskinetic RVOT, longitudinal tissue velocity at the base of the RV free wall does not reliably reflect global RV systolic function [10].

Most patients in our study had a transannular patch and severe RV dilatation; as a consequence, potential RVOT dysfunction supports the lack of correlation between TAPSE, TAPSV and RVEF when measured by MRI.

MPI is useful in high afterload with prolonged isovolumic contraction and relaxation. In high preload with low pulmonary pressure, such as with rTOF, isovolumic times are very short. We believe that in patients with RV volume overload, MPI should not be used for assessing RV systolic or diastolic function because a change in MPI could reflect a change in RV loading rather than a change in intrinsic myocardial function.

Speckle-tracking variables not described in our study could be useful for assessing RV function. Indeed Scherptong et al. [16] specifically studied RV peak systolic longitudinal strain in adult patients with rTOF and found a significant correlation between MRI RVEF and global longitudinal strain rate in a follow-up of 18 adult patients (mean age, 33 years) with TOF ($r = -0.80$ and $P < 0.01$). Dragulescu et al. [17] found very striking differences in regional myocardial function, especially in the RV longitudinal apical deformation between atrial septal defect and rTOF; while apical RV deformation was significantly increased in the atrial septal defect group, they found a very significant decrease in RV apical function in the TOF group. Further studies are needed to understand these mechanisms, but cardiopulmonary bypass-related ischaemia associated with acute change in loading conditions might be involved, as suggested in the review by Klitsie et al. [18].

Three-dimensional echocardiographic variables

We compared our volumes analyses with those from the meta-analysis by Shimada et al. [19]. Underestimation was found to be almost systematic and had a large range (−5 to −50%). However, only three studies analysed rTOF patients [20—22]: our group in 2009, Grewal et al. in 2009 and van

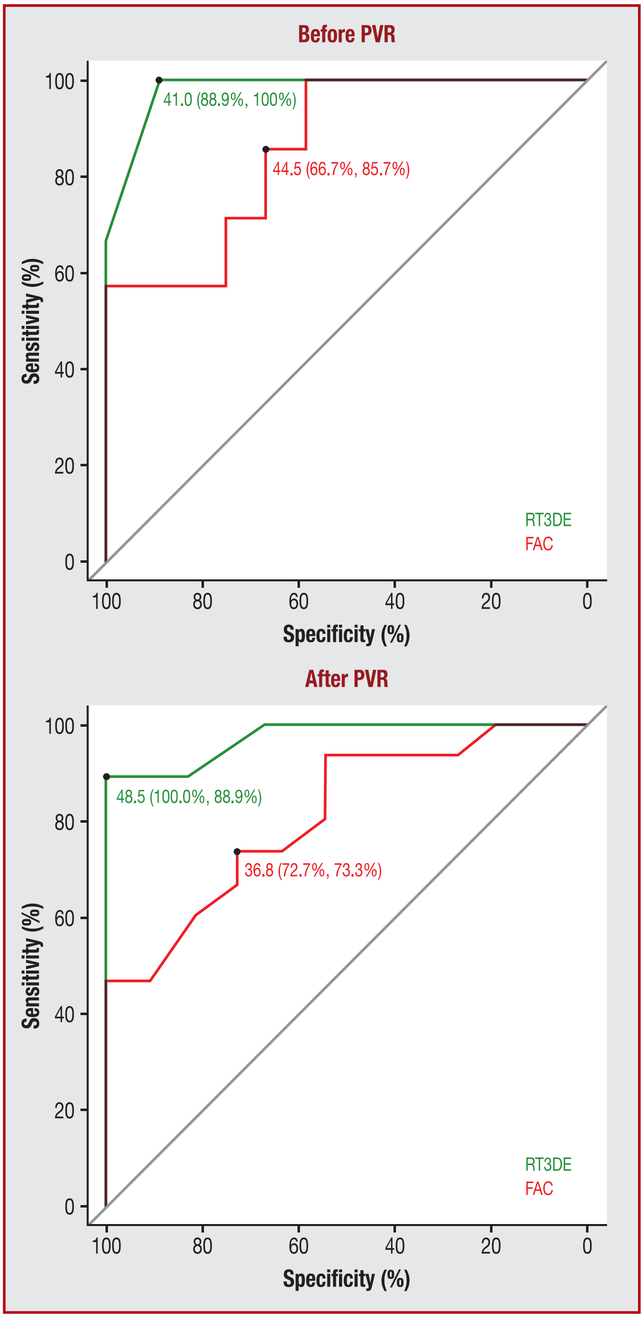

Figure 4. Receiver operating characteristic curves illustrating the capacity to detect impaired right ventricular function with fractional area of change (FAC) and real-time three-dimensional echocardiography (RT3DE), before and after pulmonary valve replacement (PVR).

der Zwaan et al. in 2010; the mean underestimations were −18.70, −25, and −34%, respectively. In our current study, underestimation was −41.6% before PVR and −41.3% after PVR. In the previous study published by our group, we found an underestimation of −18.70%, but we included both TOF patients and normal subjects, which meant that RV volumes were much smaller than in our current study. In our opinion, the accuracy of 3D echocardiography diminishes with larger RV volumes, partly because of the difficulty in including dilated RVOTs. This is supported by a recent study by

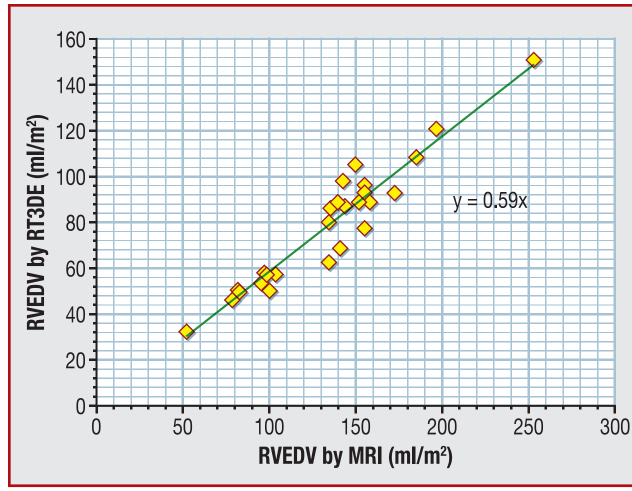

Figure 5. Right ventricular end-diastolic volume (RVEDV) correlation between magnetic resonance imaging (MRI) and real-time three-dimensional echocardiography (RT3DE), and determination of the correlation factor.

Dragulescu et al. [23], in which they found an underestimation by RT3DE of only around 7% concerning RVEDV in patients aged between 7 and 18 years with rTOF. By comparison, in an adult cohort in 2011, Crean et al. found underestimations with RT3DE of −34% for RVEDV and −42% for RVESV [24]. These underestimations may be related to a boundary tracing error, which remains the largest source of error when using 3D echocardiography methods, especially at the level of the RVOT. The use of a matrix-array transducer can also be responsible for this underestimation [19].

Despite this underestimation, agreement of 3D RV volume analyses, done by using echocardiography in our study, is excellent compared with MRI data, which was also shown by Grewal et al. and van der Zwaan et al. [21,22].

The main limitation of echocardiography (in our specific population) was the limited feasibility, which was only 46% before PVR but 57% after PVR, because of a volume decrease in RV, which permitted a better-quality acoustic window. Indeed, video clips of the two-dimensional apical four-chamber view do not predict the final RV volumes, as there is often a lack of echocardiographic resolution in the RVOT.

Right ventricle modification after PVR

In our study, after PVR, there was a significant reduction in RVEDV and RVESV and no change in RVEF assessed using MRI, as previously reported [25—28]. Few data are available concerning the evolution of echocardiographic variables for RV assessment after PVR. Knirsch et al. [29] showed that no significant change occurred in FAC or MPI, 6 months after PVR, as was shown in our study.

Another issue is the impact of pericardial constrain after pericardectomy on longitudinal function; and cardiopulmonary bypass-related ischaemia might also be concerned. Further studies are needed to understand these mechanisms.

This study compares extensive multivariable echocardiography with MRI for assessing of the RV in two different physiological conditions. A non-invasive tool to monitor RV is of crucial importance in TOF patients. PVR has shown potential to improve RV and LV haemodynamics, but the best timing for this intervention remains controversial. A global approach seems more reliable than the commonly used variables: the RV inflow contraction pattern needs to be related to the complex remodelling that encompasses the apex and the RVOT.

Conclusion

The most commonly used segmental variables used to analyse the basal free wall (TAPSE and TAPSV) appear to be insensitive regarding RV systolic function, whereas FAC, which integrates longitudinal and radial components of contraction, seems to correlate well with MRI. The correlations between RT3DE and MRI were excellent in evaluations before and after surgery, but RT3DE underestimated the RV volumes compared with MRI, and feasibility remained limited.

A global approach, using either FAC or RT3DE, gave a good estimation of RV function in patients with rTOF. This multivariable approach may reduce the need for MRI to determine RV volumes and function. However, the limitations need to be ascertained to avoid underestimating RV dilation and postponing PVR. Multimodality imaging is a good strategy for the serial follow-up of patients with rTOF, before and after PVR; it can potentially reduce the burden and costs for patients and healthcare systems, by reducing the use of MRI — which remains the gold standard for assessing the RV — when RV dilatation and impaired RV systolic function are suspected.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References

[1] Bacha EA, Scheule AM, Zurakowski D, et al. Long-term results after early primary repair of tetralogy of Fallot. J Thorac Cardiovasc Surg 2001;122:154—61.

[2] Rudski LG, Lai WW, Afilalo J, et al. Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. J Am Soc Echocardiogr 2010;23:685—713 [quiz 86—8].

[3] Sanchez-Quintana D, Anderson RH, Ho SY. Ventricular myoarchitecture in tetralogy of Fallot. Heart 1996;76:280—6.

[4] Ghio S, Recusani F, Klersy C, et al. Prognostic usefulness of the tricuspid annular plane systolic excursion in patients with congestive heart failure secondary to idiopathic or ischemic dilated cardiomyopathy. Am J Cardiol 2000;85:837—42.

[5] Kaul S, Tei C, Hopkins JM, Shah PM. Assessment of right ventricular function using two-dimensional echocardiography. Am Heart J 1984;107:526—31.

[6] Bonello B, Kilner PJ. Review of the role of cardiovascular magnetic resonance in congenital heart disease, with a focus on right ventricle assessment. Arch Cardiovasc Dis 2012;105:605—13.

[7] Iriart X, Montaudon M, Lafitte S, et al. Right ventricle three-dimensional echography in corrected tetralogy of Fallot: accuracy and variability. Eur J Echocardiogr 2009;10:784—92.

[8] Haddad F, Hunt SA, Rosenthal DN, Murphy DJ. Right ventricular function in cardiovascular disease, part I: anatomy, physiology, aging, and functional assessment of the right ventricle. Circulation 2008;117:1436—48.

[9] Bonnemains L, Stos B, Vaugrenard T, Marie PY, Odille F, Boudjemline Y. Echocardiographic right ventricle longitudinal contraction indices cannot predict ejection fraction in post-operative Fallot children. Eur Heart J Cardiovasc Imaging 2012;13:235—42.

[10] Morcos P, Vick 3rd GW, Sahn DJ, Jerosch-Herold M, Shurman A, Sheehan FH. Correlation of right ventricular ejection fraction and tricuspid annular plane systolic excursion in tetralogy of Fallot by magnetic resonance imaging. Int J Cardiovasc Imaging 2009;25:263—70.

[11] Sheehan FH, Ge S, Vick 3rd GW, et al. Three-dimensional shape analysis of right ventricular remodeling in repaired tetralogy of Fallot. Am J Cardiol 2008;101:107—13.

[12] Arnould MA, Gougnot S, Lemoine S, et al. Quantification of right ventricular function by 2D speckle imaging and three-dimensional echography. Comparison with MRI. Ann Cardiol Angeiol (Paris) 2009;58:74—85.

[13] Leong DP, Grover S, Molaee P, et al. Nonvolumetric echocardiographic indices of right ventricular systolic function: validation with cardiovascular magnetic resonance and relationship with functional capacity. Echocardiography 2012;29:455—63.

[14] Greutmann M, Tobler D, Biaggi P, et al. Echocardiography for assessment of regional and global right ventricular systolic function in adults with repaired tetralogy of Fallot. Int J Cardiol 2012;157:53—8.

[15] Kutty S, Zhou J, Gauvreau K, Trincado C, Powell AJ, Geva T. Regional dysfunction of the right ventricular outflow tract reduces the accuracy of Doppler tissue imaging assessment of global right ventricular systolic function in patients with repaired tetralogy of Fallot. J Am Soc Echocardiogr 2011;24:637—43.

[16] Scherptong RW, Mollema SA, Blom NA, et al. Right ventricular peak systolic longitudinal strain is a sensitive marker for right ventricular deterioration in adult patients with tetralogy of Fallot. Int J Cardiovasc Imaging 2009;25:669—76.

[17] Dragulescu A, Grosse-Wortmann L, Redington A, Friedberg MK, Mertens L. Differential effect of right ventricular dilatation on myocardial deformation in patients with atrial septal defects and patients after tetralogy of Fallot repair. Int J Cardiol 2013;168:803—10.

[18] Klitsie LM, Roest AA, Blom NA, ten Harkel AD. Ventricular performance after surgery for a congenital heart defect as assessed using advanced echocardiography: from doppler flow to 3D echocardiography and speckle-tracking strain imaging. Pediatr Cardiol 2014;35:3—15.

[19] Shimada YJ, Shiota M, Siegel RJ, Shiota T. Accuracy of right ventricular volumes and function determined by three-dimensional echocardiography in comparison with magnetic resonance imaging: a meta-analysis study. J Am Soc Echocardiogr 2010;23:943—53.

[20] Cheung EW, Wong WH, Cheung YF. Meta-analysis of pulmonary valve replacement after operative repair of tetralogy of Fallot. Am J Cardiol 2010;106:552—7.

[21] Grewal J, Majdalany D, Syed I, Pellikka P, Warnes CA. Three-dimensional echocardiographic assessment of right ventricular volume and function in adult patients with congenital heart disease: comparison with magnetic resonance imaging. J Am Soc Echocardiogr 2010;23:127—33.

[22] van der Zwaan HB, Helbing WA, McGhie JS, et al. Clinical value of real-time three-dimensional echocardiography for right ventricular quantification in congenital heart disease: validation with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2010;23:134—40.
[23] Dragulescu A, Grosse-Wortmann L, Fackoury C, Mertens L. Echocardiographic assessment of right ventricular volumes: a comparison of different techniques in children after surgical repair of tetralogy of Fallot. Eur Heart J Cardiovasc Imaging 2012;13:596—604.
[24] Crean AM, Maredia N, Ballard G, et al. 3D echo systematically underestimates right ventricular volumes compared to cardiovascular magnetic resonance in adult congenital heart disease patients with moderate or severe RV dilatation. J Cardiovasc Magn Reson 2011;13:78.
[25] Dragulescu A, Grosse-Wortmann L, Fackoury C, et al. Echocardiographic assessment of right ventricular volumes after surgical repair of tetralogy of Fallot: clinical validation of a new echocardiographic method. J Am Soc Echocardiogr 2011;24:1191—8.
[26] Ghez O, Tsang VT, Frigiola A, et al. Right ventricular outflow tract reconstruction for pulmonary regurgitation after repair of tetralogy of Fallot. Preliminary results. Eur J Cardiothorac Surg 2007;31:654—8.
[27] Oosterhof T, Meijboom FJ, Vliegen HW, et al. Long-term follow-up of homograft function after pulmonary valve replacement in patients with tetralogy of Fallot. Eur Heart J 2006;27:1478—84.
[28] Therrien J, Provost Y, Merchant N, Williams W, Colman J, Webb G. Optimal timing for pulmonary valve replacement in adults after tetralogy of Fallot repair. Am J Cardiol 2005;95:779—82.
[29] Knirsch W, Dodge-Khatami A, Kadner A, et al. Assessment of myocardial function in pediatric patients with operated tetralogy of Fallot: preliminary results with 2D strain echocardiography. Pediatr Cardiol 2008;29:718—25.