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Evaluation of right atrial dysfunction in patients with corrected tetralogy of Fallot using 3D speckle-tracking echocardiography

Insights from the CSONGRAD Registry and MAGYAR-Path Study

Three-dimensional speckle-tracking echocardiography encompasses the benefits of speckle tracking and three-dimensional echocardiography allowing visualization of the heart as it is: a three-dimensional organ [1–3]. While ventricular and atrial volumetric measurements can be performed by direct volumetric real-time three-dimensional echocardiography, three-dimensional speckle-tracking echocardiography allows for a detailed evaluation of myocardial deformation over volumetric assessments using three-dimensional strain analysis as well [1–3]. The clinical relevance of evaluating myocardial deformation in adults with corrected tetralogy of Fallot is increasingly recognized [4–6]. In recent publications, impairment in left and right ventricular deformations could be demonstrated in adult patients with corrected tetralogy of Fallot [4–6]. However, little is known about right atrial function in corrected tetralogy of Fallot. Therefore, the present study aimed to assess three-dimensional speckle-tracking echocardiography-derived right atrial volumetric and strain parameters in adult patients with corrected tetralogy of Fallot and to compare them with those of healthy matched controls.

Patients and methods

Patient population

Since 1961, more than 2,700 patients with different congenital heart diseases have been treated and/or operated on at the Department of Pediatrics, Department of Heart Surgery, and 2nd Department of Medicine and Cardiology Center at the University of Szeged. A registry has been created named after Csongrád County, where the University of Szeged is located, in which all the available demographic, clinical, and prognostic data of these patients have been summarized – the CSONGRAD Registry: Registry of *C(S)ongenital* Car*d*i*ac* *D*isease Patients at the University of Szeged. From this registry, 17 consecutive adult patients with corrected tetralogy of Fallot were enrolled in the present study. Patients had undergone isolated tetralogy of Fallot repair at 4.2 ± 2.3 years of age. Their results were compared with 18 age- and gender-matched healthy controls. All subjects with known diseases were excluded from the control group. Complete two-dimensional Doppler echocardiography and three-dimensional speckle-tracking echocardiography were performed in all corrected tetralogy of Fallot cases and controls. The results presented here are part of the MAGYAR-Path Study (*M*otion *A*nalysis of the Heart and *G*reat Vessels b*y* Three-dimension*a*l Speckle-T*r*acking Echocardiography in *P*athological Cases). This study was designed to evaluate the usefulness and diagnostic and prognostic value of three-dimensional speckle-tracking echocardiography-derived volumetric, strain, and rotational parameters in pathological cases at our center (*magyar* means *Hungarian*). Informed consent was obtained from each patient and the study protocol conformed to the ethical guidelines of the 1975 Dec-

Table 1 Method to calculate right atrial stroke volumes and emptying fractions in each phase of right atrial motion

Functions	Stroke volumes (ml)	Emptying fractions (%)
Reservoir function	Total SV = V_{max}-V_{min}	Total EF = Total SV/V_{max}
Conduit function	Passive SV = V_{max}-V_{preA}	Passive EF= Passive SV/V_{max}
Active contraction	Active SV = V_{preA}-V_{min}	Active EF = Active SV/V_{preA}

EF emptying fraction, *SV* stroke volume, V_{max} maximum right atrial volume, V_{min} minimum right atrial volume, V_{preA} right atrial volume before atrial contraction.

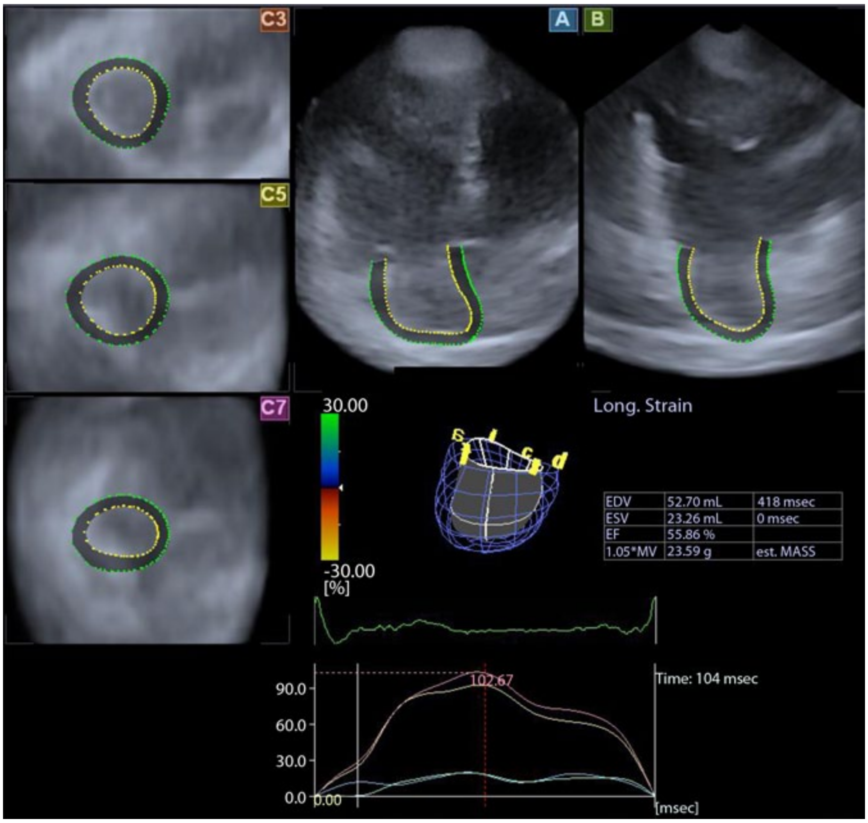

Fig. 1 ▲ Images from three-dimensional full-volume dataset demonstrating the right atrium in a patient with corrected tetralogy of Fallot: (*A*) apical four-chamber view, (*B*) apical two-chamber view, (*C3*) parasternal short-axis view at basal, (*C5*) mid-, and (*C7*) superior right atrial level. Three-dimensional cast of the right atrium and calculated parameters based on three-dimensional speckle-tracking echocardiographic analysis are also presented.

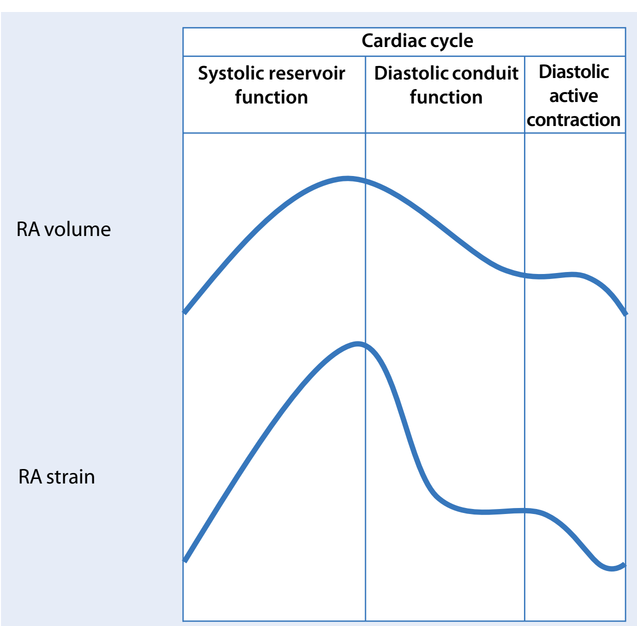

Fig. 2 ◀ Schematic figure demonstrating volumetric and strain changes during the three functions of the right atrium (*RA*) and their relation to the cardiac cycle

laration of Helsinki, as reflected in a priori approval by the institution's human research committee.

Two-dimensional echocardiography

Complete two-dimensional Doppler echocardiographic examinations were performed in all cases by commercially available Toshiba Artida^{TM} echocardiography equipment (Toshiba Medical Systems, Tokyo, Japan) with a PST-30SBP (1–5 MHz) phased-array transducer. Left ventricular and left atrial dimensions, volumes, and ejection fraction were measured with the Teichholz method in parasternal long-axis view in all cases. The degree of mitral and tricuspid regurgitations were visually quantified by color Doppler echocardiography. Tricuspid annular plane systolic excursion (TAPSE) and right ventricular fractional area change (RV-FAC) were also calculated.

Three-dimensional speckle-tracking echocardiography-derived right atrial volumetric measurements

All patients underwent three-dimensional echocardiographic imaging immediately after a two-dimensional echocardiographic study using a commercially available PST-25SX matrix-array transducer (Toshiba Medical Systems, Tokyo, Japan) with three-dimensional speckle-tracking echocardiography capability [1–3]. To create full-volume three-dimensional datasets, six wedge-shaped subvolumes were acquired from an apical window over six consecutive cardiac cycles within a single breath-hold and during a constant R-R interval. The sector width was decreased as much as possible to improve the temporal and spatial resolution of the image in order to obtain a full-volume three-dimensional dataset of the right atrium with optimal border delineation. Chamber quantification by three-dimensional speckle-tracking echocardiography was performed off-line using the 3D Wall Motion Tracking software, version 2.5 (Toshiba Medical Systems, Tokyo, Japan). Three-dimensional echocardiographic datasets were displayed in

Abstract · Zusammenfassung

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Evaluation of right atrial dysfunction in patients with corrected tetralogy of Fallot using 3D speckle-tracking echocardiography. Insights from the CSONGRAD Registry and MAGYAR-Path Study

Abstract

Background. In recent studies, alterations in ventricular deformations were demonstrated in adult patients with corrected tetralogy of Fallot by three-dimensional speckle-tracking echocardiography. The present study was designed to assess three-dimensional speckle-tracking echocardiography-derived right atrial volumetric and strain parameters in corrected tetralogy of Fallot.

Methods. A total of 17 patients with corrected tetralogy of Fallot were included in the study. Their results were compared with 18 age- and gender-matched healthy controls. Complete two-dimensional echocardiography and three-dimensional speckle-tracking echocardiography were performed in all cases.

Results. Significantly increased right atrial volumes respecting heart cycle were detected in patients with corrected tetralogy of Fallot. Total and passive atrial emptying fractions proved to be significantly decreased in patients with corrected tetralogy of Fallot (26.4 ± 12.4 % vs. 39.1 ± 8.8 %, p = 0.001 and 11.2 ± 6.8 % vs. 19.8 ± 9.0 %, p = 0.003, respectively). Global and mean segmental peak longitudinal (17.3 ± 9.2 % vs. 30.8 ± 11.2 %, p = 0.0007 and 20.6 ± 10.7 % vs. 34.4 ± 10.5 %, p = 0.0005) and area strains (20.1 ± 17.6 % vs. 41.0 ± 19.8 %, p = 0.004 and 28.1 ± 19.8 % vs. 49.1 ± 19.7 %, p = 0.004) as well as global radial peak strain (– 9.1 ± 5.1 % vs. – 15.0 ± 10.0 %, p = 0.05) were reduced in patients with corrected tetralogy of Fallot compared with controls.

Conclusions. The complexity of right atrial dysfunction can be demonstrated by three-dimensional speckle-tracking echocardiography in patients with corrected tetralogy of Fallot.

Keywords

Echocardiography · Function · Right atrial · Three-dimensional · Speckle-tracking echocardiography

Untersuchung rechtsatrialer Funktionsstörungen mittels 3-D-Speckle-Tracking-Echokardiographie bei Patienten mit korrigierter Fallot-Tetralogie. Erkenntnisse aus dem CSONGRAD-Register und der MAGYAR-Path-Studie

Zusammenfassung

Hintergrund. In aktuellen Studien ließen sich Veränderungen der ventrikulären Verformbarkeit bei erwachsenen Patienten mit korrigierter Fallot-Tetralogie durch dreidimensionale Speckle-Tracking-Echokardiographie nachweisen. Die vorliegende Studie diente der Untersuchung von rechtsatrialen volumetrischen und Deformationsparametern, die mittels dreidimensionaler Speckle-Tracking-Echokardiographie bei korrigierter Fallot-Tetralogie erhoben wurden.

Methoden. Es wurden 17 Patienten mit korrigierter Fallot-Tetralogie in die Studie eingeschlossen. Deren Ergebnisse wurden mit 18 nach Alter und Geschlecht entsprechend ausgewählten Kontrollen verglichen. In allen Fällen wurden eine vollständige zweidimensionale Echokardiographie und eine dreidimensionale Speckle-Tracking-Echokardiographie durchgeführt.

Ergebnisse. Bei den Patienten mit korrigierter Fallot-Tetralogie wurden signifikant erhöhte rechtsatriale Volumina unter Berücksichtigung des Herzzyklus festgestellt. Die Gesamt- und die passive atriale Entleerungsfraktion stellten sich bei Patienten mit korrigierter Fallot-Tetralogie als signifikant vermindert heraus (26,4 ± 12,4 % vs. 39,1 ± 8,8 %; p = 0,001 bzw. 11,2 ± 6,8 % vs. 19,8 ± 9,0 %; p = 0,003). Die globale und mittlere segmentale longitudinale Spitzen- (17,3 ± 9,2 % vs. 30,8 ± 11,2 %; p = 0,0007 und 20,6 ± 10,7 % vs. 34,4 ± 10,5 %; p = 0,0005) und flächige Deformation (20,1 ± 17,6 % vs. 41,0 ± 19,8 %; p = 0,004 und 28,1 ± 19,8 % vs. 49,1 ± 19,7 %; p = 0,004) sowie die globale radiale Spitzendeformation (– 9,1 ± 5,1 % vs. – 15,0 ± 10,0 %; p = 0,05) erwiesen sich bei Patienten mit korrigierter Fallot-Tetralogie gegenüber den Kontrollen als vermindert.

Schlussfolgerung. Mit der dreidimensionalen Speckle-Tracking-Echokardiographie konnte die Komplexität rechtsatrialer Funktionsstörungen bei Patienten mit korrigierter Fallot-Tetralogie gezeigt werden.

Schlüsselwörter

Echokardiographie · Funktion · Rechtsventrikulär · Dreidimensional · Speckle-Tracking-Verfahren

apical four-chamber and two-chamber views and three short-axis views in basal, mid-atrial, and superior right atrial regions, respectively (■ **Fig. 1**). In the apical four-chamber and two-chamber views, the endocardial border was traced by setting multiple reference points by the user starting at the base of the right atrium at the tricuspid valve level, moving toward the lowest point of the right atrium, and excluding the right atrial appendage and venae cavae from the right atrial cavity, as demonstrated previously for the left atrium [7–9] (■ **Fig. 1**). The epicardial border was adjusted manually or by setting a default thickness for the myocardium. Three-dimensional wall motion tracking, which is based on a three-dimensional block-matching algorithm, was automatically performed by the software following detection of the right atrial borders at the end-diastolic reference frame. The user could correct the shape of the right atrium if necessary throughout the entire cardiac cycle. The following volumetric calculations were performed for the right atrium respecting cardiac cycle (■ **Fig. 2**):

1. Maximum right atrial volume (V_{max}) was measured at endsystole, the time at which the right atrial volume was the largest just before tricuspid valve opening
2. Minimum right atrial volume (V_{min}) was measured at enddiastole, the time at which the right atrial volume was the smallest before tricuspid valve closure

Table 2 Clinical and two-dimensional echocardiographic data of patients with corrected tetralogy of Fallot and of controls

	cTOF patients ($n=17$)	Controls ($n=18$)	p
Risk factors			
Age (years)	38.2 ± 11.8	36.4 ± 9.8	0.63
Male gender (%)	7 (41)	10 (56)	0.51
Two-dimensional echocardiography			
LA diameter (mm)	41.8 ± 6.60	32.7 ± 3.4	< 0.0001
LV end-diastolic diameter (mm)	55.8 ± 20.3	47.4 ± 7.0	0.11
LV end-diastolic volume (ml)	117.2 ± 31.6	96.8 ± 17.1	0.02
LV end-systolic diameter (mm)	33.2 ± 7.3	29.8 ± 4.3	0.10
LV end-systolic volume (ml)	45.3 ± 24.0	33.9 ± 10.9	0.08
Interventricular septum (mm)	9.8 ± 1.5	9.5 ± 2.1	0.64
LV posterior wall (mm)	9.7 ± 1.5	9.5 ± 2.5	0.79
LV ejection fraction (%)	62.3 ± 12.0	65.4 ± 7.1	0.35

LA left atrial, *LV* left ventricular, *cTOF* corrected tetralogy of Fallot.

Table 3 Comparison of 3DSTE-derived volumetric and volume-based functional right atrial parameters in patients with corrected tetralogy of Fallot and in controls

	cTOF patients ($n=17$)	Controls ($n=18$)	p
Calculated volumes (ml)			
Maximum RA volume (V_{max})	64.9 ± 33.8	37.8 ± 10.1	0.003
Minimum RA volume (V_{min})	49.8 ± 32.8	23.1 ± 7.9	0.002
RA volume before atrial contraction (V_{preA})	57.9 ± 32.1	30.2 ± 9.0	0.001
Stroke volumes (ml)			
Total atrial SV	15.1 ± 6.4	14.6 ± 4.8	0.79
Passive atrial SV	6.9 ± 4.7	7.5 ± 4.3	0.70
Active atrial SV	8.1 ± 5.1	7.1 ± 3.3	0.49
Emptying fractions (%)			
Total atrial EF	26.4 ± 12.4	39.1 ± 8.8	0.001
Passive atrial EF	11.2 ± 6.8	19.8 ± 9.0	0.003
Active atrial EF	17.3 ± 11.9	23.7 ± 10.3	0.10

3DSTE three-dimensional speckle-tracking echocardiography, *RA* right atrial, V_{max} maximum right atrial volume, V_{min} minimum right atrial volume, V_{preA} right atrial volume before atrial contraction, *SV* stroke volume, *EF* emptying fraction, *cTOF* corrected tetralogy of Fallot.

Table 4 Comparison of 3DSTE-derived global and segmental peak right atrial strain parameters in patients with corrected tetralogy of Fallot and in controls

	cTOF patients ($n=17$)	Controls ($n=18$)	p
Global strains			
Radial strain (%)	−9.1 ± 5.1	−15.0 ± 10.0	0.05
Circumferential strain (%)	7.5 ± 8.7	12.0 ± 8.4	0.13
Longitudinal strain (%)	17.3 ± 9.2	30.8 ± 11.2	0.0007
3D strain (%)	−4.5 ± 3.7	−6.7 ± 5.6	0.18
Area strain (%)	20.1 ± 17.6	41.0 ± 19.8	0.004
Mean segmental strains			
Radial strain (%)	−16.4 ± 6.2	−19.3 ± 8.4	0.26
Circumferential strain (%)	12.2 ± 8.9	17.7 ± 8.8	0.08
Longitudinal strain (%)	20.6 ± 10.7	34.4 ± 10.5	0.0005
3D strain (%)	−10.3 ± 4.9	−12.2 ± 5.8	0.30
Area strain (%)	28.1 ± 19.8	49.1 ± 19.7	0.004

3DSTE three-dimensional speckle-tracking echocardiography, *3D* three-dimensional, *cTOF* corrected tetralogy of Fallot.

Table 5 Comparison of 3DSTE-derived segmented peak right atrial strain parameters in patients with corrected tetralogy of Fallot and in controls

	cTOF patients ($n=17$)	Controls ($n=18$)	p
RS_{basal} (%)	−16.1 ± 9.0	−17.3 ± 7.6	0.67
$RS_{mid\text{-}atrial}$ (%)	−17.4 ± 7.5	−18.3 ± 10.7	0.78
$RS_{superior}$ (%)	−15.2 ± 9.8	−23.6 ± 12.1	0.03
CS_{basal} (%)	10.9 ± 10.0	24.2 ± 11.4	0.0009
$CS_{mid\text{-}atrial}$ (%)	11.0 ± 8.2	15.1 ± 8.9	0.17
$CS_{superior}$ (%)	16.7 ± 14.5	11.0 ± 12.1	0.21
LS_{basal} (%)	19.8 ± 12.4	32.7 ± 12.3	0.004
$LS_{mid\text{-}atrial}$ (%)	28.8 ± 16.1	49.6 ± 15.3	0.0004
$LS_{superior}$ (%)	10.7 ± 7.7	14.2 ± 12.5	0.33
$3DS_{basal}$ (%)	−10.2 ± 5.5	−10.6 ± 5.7	0.83
$3DS_{mid\text{-}atrial}$ (%)	−10.7 ± 5.5	−10.2 ± 6.5	0.81
$3DS_{superior}$ (%)	−10.0 ± 5.9	−17.7 ± 10.9	0.01
AS_{basal} (%)	21.9 ± 17.4	50.1 ± 18.0	< 0.0001
$AS_{mid\text{-}atrial}$ (%)	35.3 ± 25.7	64.3 ± 26.0	0.002
$AS_{superior}$ (%)	28.9 ± 23.3	25.0 ± 26.1	0.64

3DSTE three-dimensional speckle-tracking echocardiography, *RS* radial strain, *CS* circumferential strain, *LS* longitudinal strain, *3DS* three-dimensional strain, *AS* area strain, *cTOF* corrected tetralogy of Fallot.

3. Right atrial volume before atrial contraction (V_{preA}), the last frame before tricuspid valve reopening or at the time of the P wave on the electrocardiogram

From the three volumes, several parameters characterizing each phase of right atrial function could be assessed (**Table. 1**).

Three-dimensional speckle-tracking echocardiography-derived right atrial strain measurements

The following global, mean segmental, and segmented (basal, mid-atrial, and superior) peak (characterizing right atrial reservoir function) and pre-atrial contraction (characterizing right atrial active contraction function) strain parameters were routinely measured by the software in a semi-automatic fashion from the three-dimensional echocardiographic dataset (**Fig. 2**):

1. Longitudinal strain in the direction tangential to the endocardial contour
2. Circumferential strain in circumferential direction

Table 6 Comparison of 3DSTE-derived global and segmental pre-atrial contraction right atrial strain parameters in patients with corrected tetralogy of Fallot and in controls

	cTOF patients (n = 17)	Controls (n = 18)	p
Global strains			
Radial strain (%)	− 5.7 ± 4.3	− 8.0 ± 8.3	0.31
Circumferential strain (%)	3.9 ± 6.9	10.8 ± 11.0	0.03
Longitudinal strain (%)	5.7 ± 6.3	8.7 ± 9.6	0.29
3D strain (%)	− 1.5 ± 4.2	− 5.6 ± 5.4	0.02
Area strain (%)	10.0 ± 13.2	16.6 ± 17.0	0.21
Mean segmental strains			
Radial strain (%)	− 7.3 ± 5.3	− 9.0 ± 5.4	0.34
Circumferential strain (%)	7.4 ± 9.2	3.5 ± 9.8	0.24
Longitudinal strain (%)	7.3 ± 5.2	9.3 ± 6.4	0.33
3D strain (%)	− 4.6 ± 4.7	− 7.1 ± 4.8	0.13
Area strain (%)	13.5 ± 13.2	21.3 ± 15.6	0.12

3DSTE three-dimensional speckle-tracking echocardiography, *3D* three-dimensional, *cTOF* corrected tetralogy of Fallot.

Table 7 Comparison of 3DSTE-derived segmented pre-atrial contraction right atrial strain parameters in patients with corrected tetralogy of Fallot and in controls

	cTOF patients (n = 17)	Controls (n = 18)	p
RS_{basal} (%)	− 7.3 ± 7.3	− 9.6 ± 6.5	0.32
$RS_{mid\text{-}atrial}$ (%)	− 7.8 ± 5.2	− 8.5 ± 6.0	0.69
$RS_{superior}$ (%)	− 6.5 ± 8.3	− 8.9 ± 7.1	0.36
CS_{basal} (%)	5.3 ± 8.4	16.8 ± 9.8	0.0008
$CS_{mid\text{-}atrial}$ (%)	5.7 ± 6.4	11.4 ± 8.8	0.04
$CS_{superior}$ (%)	7.1 ± 9.6	9.7 ± 13.2	0.52
LS_{basal} (%)	7.1 ± 4.0	6.7 ± 5.7	0.83
$LS_{mid\text{-}atrial}$ (%)	9.4 ± 8.8	9.7 ± 7.5	0.92
$LS_{superior}$ (%)	5.6 ± 6.3	10.2 ± 9.6	0.11
$3DS_{basal}$ (%)	− 4.9 ± 5.8	− 7.7 ± 5.7	0.17
$3DS_{mid\text{-}atrial}$ (%)	− 4.6 ± 4.6	− 6.0 ± 4.6	0.37
$3DS_{superior}$ (%)	− 4.4 ± 8.5	− 7.5 ± 6.0	0.21
AS_{basal} (%)	11.9 ± 12.7	19.9 ± 11.2	0.06
$AS_{mid\text{-}atrial}$ (%)	16.0 ± 16.5	24.3 ± 14.8	0.13
$AS_{superior}$ (%)	12.7 ± 16.4	18.7 ± 31.9	0.50

3DSTE three-dimensional speckle-tracking echocardiography, *RS* radial strain, *CS* circumferential strain, *LS* longitudinal strain, *3DS* three-dimensional strain, *AS* area strain, *cTOF* corrected tetralogy of Fallot.

3. Radial strain in perpendicular direction to the endocardial contour
4. Three-dimensional strain defined as strain in the wall thickening direction
5. Area strain as a ratio of endocardial area change during the cardiac cycle

Statistical analysis

All data are reported as mean ±standard deviation. A value of $p < 0.05$ was considered to be statistically significant. For comparing variables, the Student's t test, chi-square analysis, and Fisher's exact test were used. Pearson's coefficient was used for interobserver and intraobserver correlations. Intra- and interobserver agreements were studied according to the Bland and Altman method. MedCalc software was used for statistical calculations (MedCalc, Mariakerke, Belgium).

Results

Two-dimensional echocardiographic data

Clinical and standard two-dimensional echocardiographic data are summarized in **Table. 2**. Significant (≥ grade 2) mitral and tricuspid regurgitations could be detected in one (6 %) and six (35 %) patients with corrected tetralogy of Fallot, respectively. None of the healthy controls showed significant (≥ grade 2) mitral and tricuspid regurgitations. The TAPSE and RV-FAC values of patients with corrected tetralogy of Fallot were 17.8 ± 4.1 mm and 33.1 ± 4.3, respectively.

Three-dimensional speckle-tracking echocardiography-derived volumes and volume-based functional properties

Significantly increased right atrial volumes respecting the heart cycle were detected in patients with corrected tetralogy of Fallot. Total and passive atrial emptying fractions proved to be significantly decreased in patients with corrected tetralogy of Fallot (**Table. 3**).

Three-dimensional speckle-tracking echocardiography-derived peak strain parameters

Global and mean segmental peak longitudinal and area strain parameters and global peak radial strain were reduced in patients with corrected tetralogy of Fallot compared with controls (**Table. 4**). Segmental peak strain parameters are summarized in **Table. 5**.

Three-dimensional speckle-tracking echocardiography-derived pre-atrial contraction strain parameters

Global pre-atrial contraction circumferential and three-dimensional strain parameters were found to be reduced in patients with corrected tetralogy of Fallot compared with controls (**Table. 6**). Segmental pre-atrial contraction strain parameters are summarized in **Table. 7**.

Reproducibility of volumetric three-dimensional speckle-tracking echocardiography measurements

The mean ± standard deviation difference in values obtained in two measurements by the same observer for the calculation of three-dimensional speckle-tracking echocardiography-derived peak maximum and minimum right atrial volumes and right atrial volume before atrial contraction in patients with corrected tetralogy of Fallot was − 2.0 ± 10.3 ml, − 2.3 ± 11.3 ml, and − 3.0 ± 10.8 ml, respectively. Correlation coefficients between the measurements of two observ-

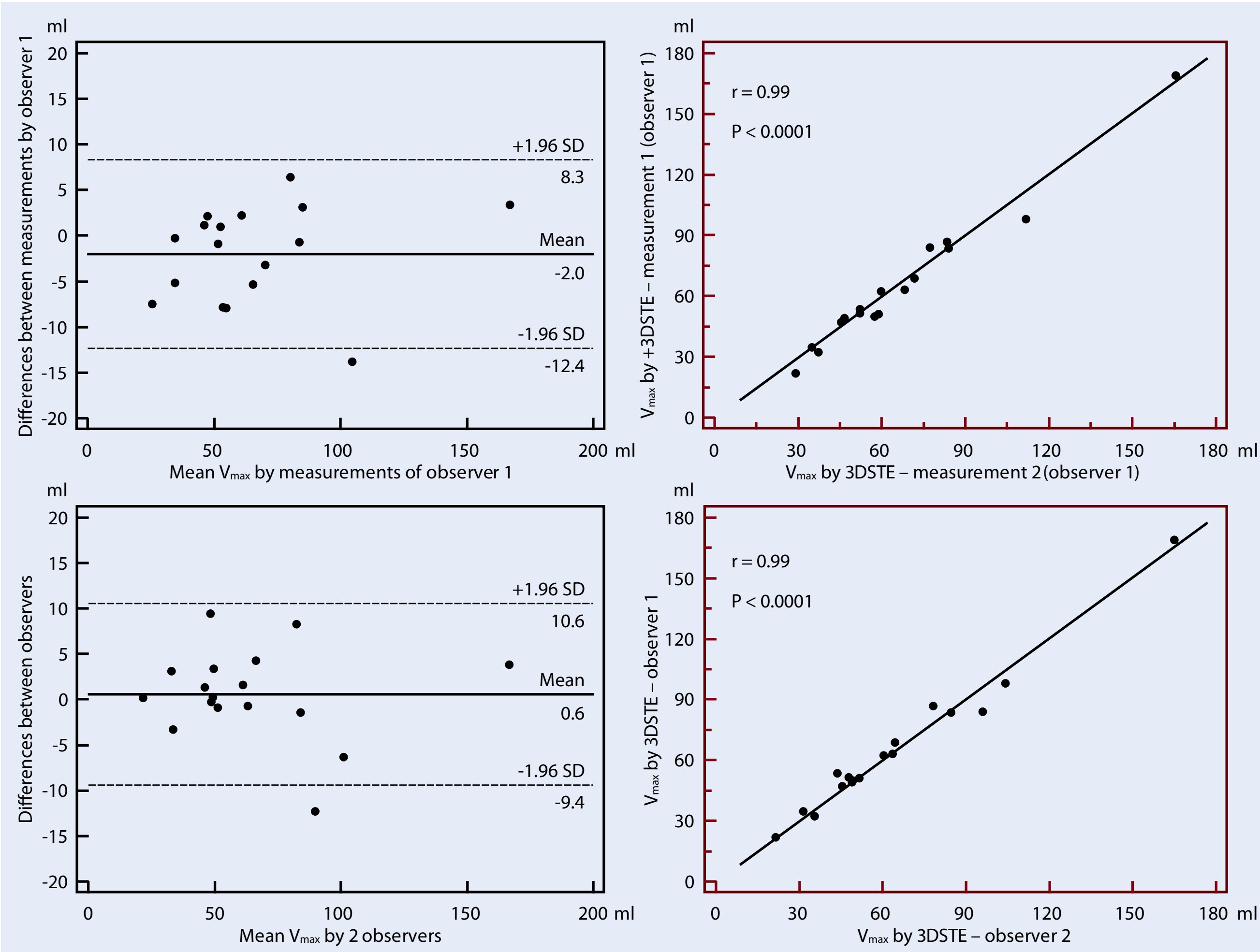

Fig. 3 ▲ Intraobserver (*upper graphs*) and interobserver (*lower graphs*) agreements and correlations for measuring peak V_{max} by three-dimensional speckle-tracking echocardiography. (*V_{max}* maximum right atrial volume, *3DSTE* three-dimensional speckle-tracking echocardiography)

ers were 0.99, 0.98, and 0.99 ($p<0.0001$), respectively (**Figs. 3, 4, and 5;** intraobserver agreement). The mean ± standard deviation difference in values obtained by two observers for three-dimensional speckle-tracking echocardiography-derived peak maximum and minimum right atrial volumes and right atrial volume before atrial contraction in patients with corrected tetralogy of Fallot was 0.6 ± 10.0 ml, −1.5 ± 9.2 ml, and −2.3 ± 20.4 ml, respectively. Correlation coefficients between these independent measurements by the same observer were 0.99, 0.99, and 0.95 ($p<0.0001$), respectively (**Figs. 3, 4, and 5;** interobserver agreement).

Discussion

To the best of the authors' knowledge, this is the first study in which right atrial volumetric and functional changes could be demonstrated in patients with corrected tetralogy of Fallot by three-dimensional speckle-tracking echocardiography. Results strengthen previous findings that three-dimensional speckle-tracking echocardiography enables a more detailed evaluation of atrial function respecting its motion during heart cycle. Increased right atrial volumes and decreased right atrial emptying fractions were found together with alterations in right atrial global, mean segmental, and segmental peak and pre-atrial contraction strains in patients with corrected tetralogy of Fallot.

Today, computed tomography, cardiac magnetic resonance imaging, as well as transthoracic and transesophageal volumetric real-time three-dimensional echocardiography can be used in clinical practice to provide reliable information on right atrial structures and function [10]. Normative values for right atrial volumes and function were demonstrated by volumetric real-time three-dimensional echocardiography and two-dimensional speckle-tracking echocardiography in a relatively large cohort of healthy subjects with a wide age range [11]. Three-dimensional speckle-tracking echocardiography is a novel cardiac imaging technique for assessing complex cardiac motion based on frame-to-frame tracking of ultrasonic speckles in three dimensions [1–3]. This methodology has been confirmed to be

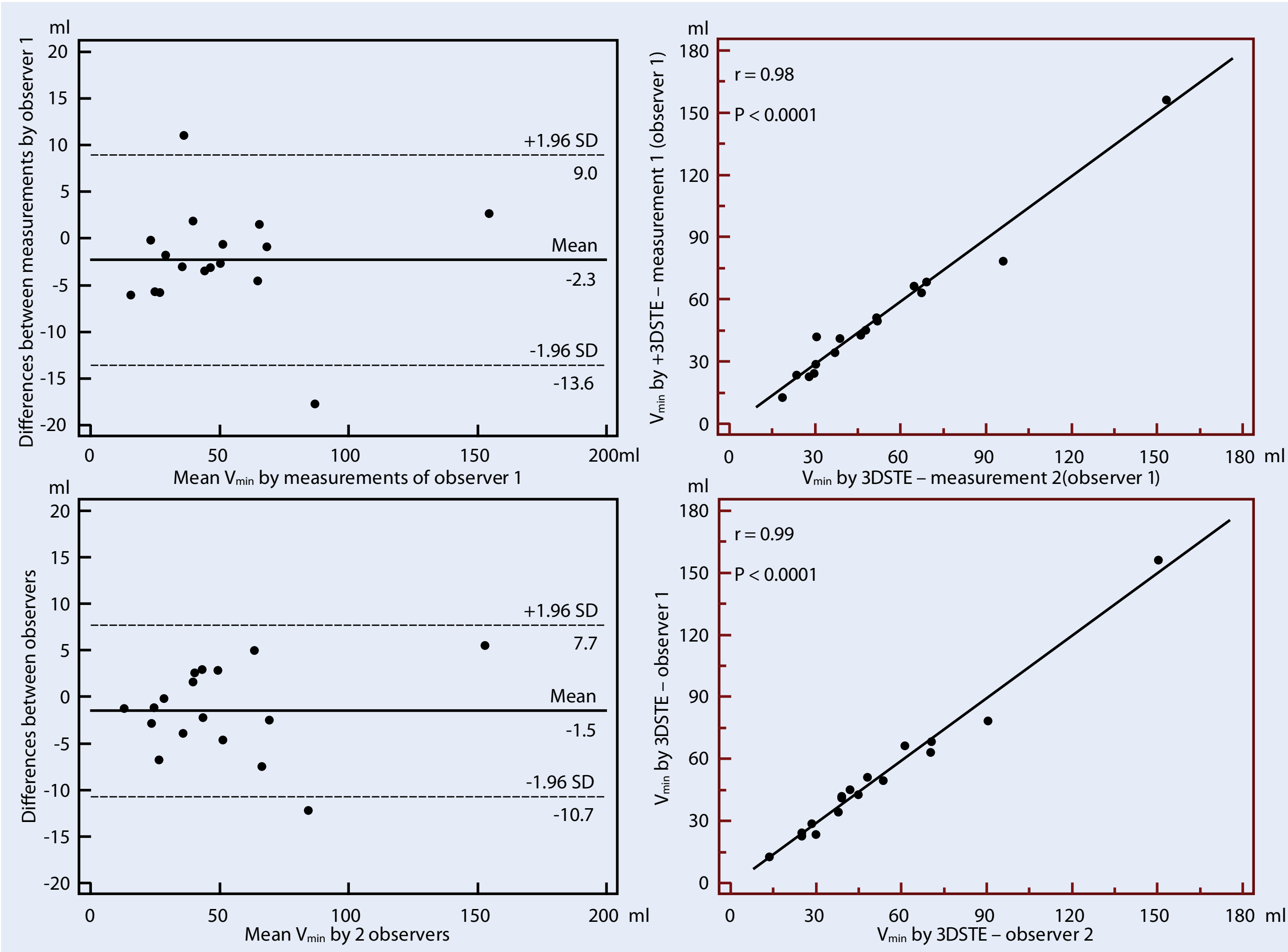

Fig. 4 ▲ Intraobserver (*upper graphs*) and interobserver (*lower graphs*) agreements and correlations for measuring peak V_{min} by three-dimensional speckle-tracking echocardiography. (V_{min} minimum right atrial volume, *3DSTE* three-dimensional speckle-tracking echocardiography)

a promising tool for the quantification of left ventricular [12–14] and left atrial [7, 8, 15] volumes. Moreover, global and regional left ventricular [16–18], right ventricular [4], and left atrial [8, 9, 19] myocardial deformation can also be assessed by three-dimensional strain analysis. It is possible to measure dyssynchrony parameters by three-dimensional speckle-tracking echocardiography, as demonstrated for the left ventricle [20–22], left atrium [19], and right ventricle [4]. However, volumetric and functional evaluations of the right atrium have not been assessed by three-dimensional speckle-tracking echocardiography.

In recent studies, alterations in ventricular deformations could be demonstrated in adult patients with corrected tetralogy of Fallot using three-dimensional speckle-tracking echocardiography [4–6]. Impaired global and regional left ventricular three-dimensional systolic strain, mechanical dyssynchrony, and reduced twist were found to be related to reduced septal curvature in patients with repaired tetralogy of Fallot with and without pulmonary valve replacement [5]. In another study of adults after tetralogy of Fallot repair, three-dimensional right ventricular deformation was found to be impaired in association with right ventricular dyssynchrony, volume overloading, and reduced ejection fraction [4]. However, atrial deformation has not been assessed by three-dimensional speckle-tracking echocardiography in corrected tetralogy of Fallot.

During evaluation of the right atrium, all three functions were assessed, including: (1) reservoir function by total atrial stroke volume and total atrial emptying fraction together with global, mean segmental, and segmental basal, mid-atrial, and superior peak strain parameters; (2) conduit function by passive atrial stroke volume and passive atrial emptying fraction; and (3) active contraction by active atrial stroke volume and active atrial emptying fraction together with global, mean segmental, and segmental basal, mid-atrial, and superior pre-atrial contraction strain parameters. In our volumetric measurements, reduced reservoir (decreased total atrial emptying fraction) and conduit (reduced passive atrial emptying fraction) functions could be demonstrated. Alterations in specific global, mean segmental, and segmental right atrial peak strains confirmed a diminished right atrial reservoir function. While active atrial stroke volume and emptying showed no significant alterations, global and specific segmental right atrial pre-atrial contraction

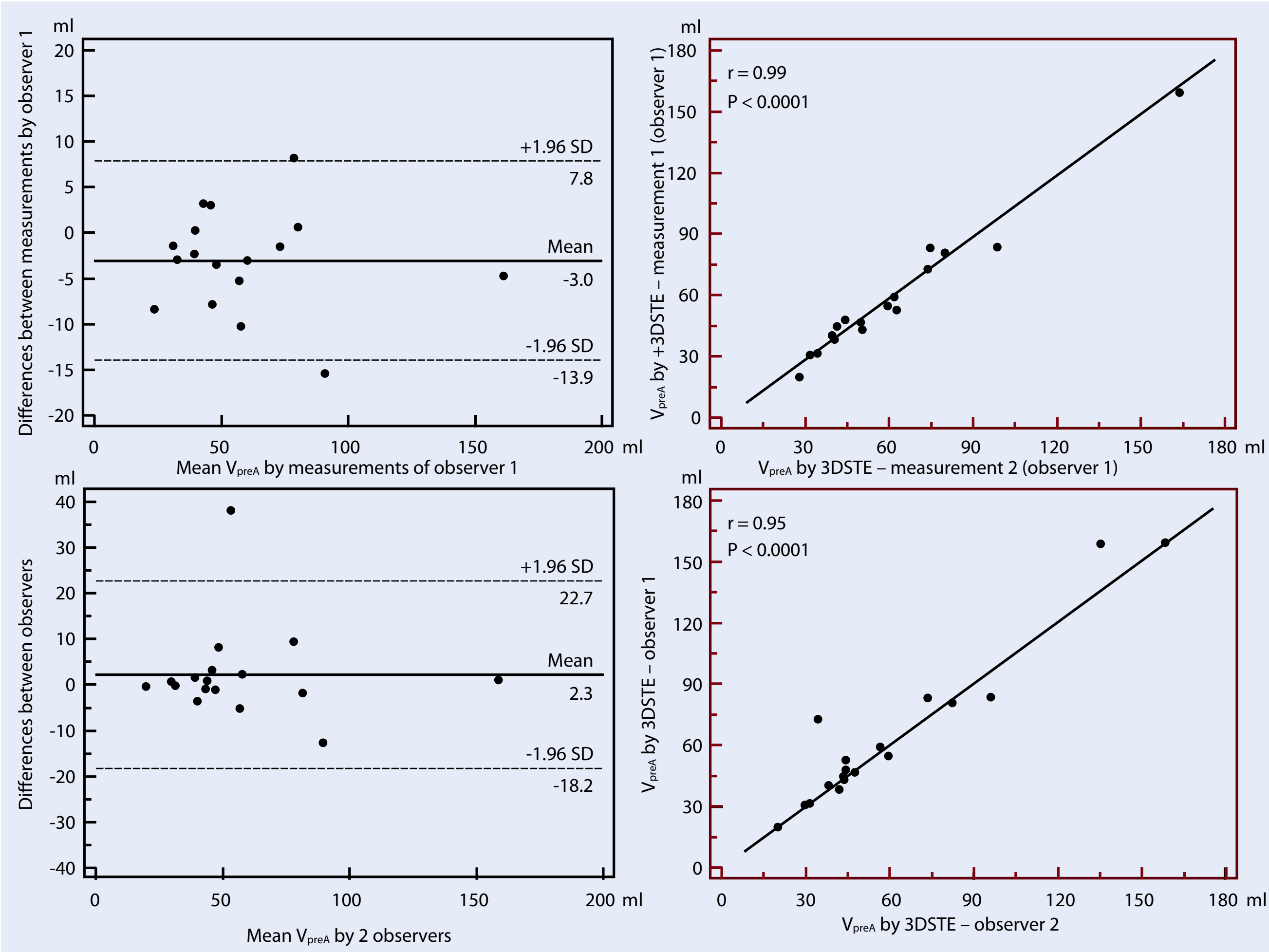

Fig. 5 ▲ Intraobserver (*upper graphs*) and interobserver (*lower graphs*) agreements and correlations for measuring peak V_{preA} by three-dimensional speckle-tracking echocardiography. (V_{preA} right atrial volume before atrial contraction, *3DSTE* three-dimensional speckle-tracking echocardiography)

strains were reduced, suggesting changes in the active contraction phase as well. Reduced right atrial function could be explained by the hydrodynamic effects of pulmonary and/or tricuspid regurgitation, scar in the right atrium, injured pericardium, and the disease itself [23]. However, further studies are warranted to confirm our findings.

Limitations

The following important limitations should be taken into consideration when interpreting our results:

1. The right atrial appendage, caval veins, and coronary sinus were excluded from the calculations of right atrial volumes and functional properties.
2. The current image quality obtained by three-dimensional speckle-tracking echocardiography is lower than for two-dimensional echocardiography due to the low temporal and spatial image resolutions.
3. Three-dimensional speckle-tracking echocardiography was used for calculation of volumetric [7, 8, 14] and strain [8, 9, 19] parameters of the right atrium that were validated for the left atrium [7–9, 14, 19]. However, further validation studies are warranted by other imaging tools for both atria.
4. Reproducibility assessments were calculated only for peak volumetric right atrial data owing to the fact that volumetric and strain assessments were performed from the same three-dimensional echocardiographic datasets.
5. Right atrial dilation could have resulted from tricuspid regurgitation, which could also affect right atrial function.
6. Left ventricular, left atrial, and right ventricular deformations were not assessed by three-dimensional speckle-tracking echocardiography in this study.
7. We did not aim to find the relationship between morphology and function of the right ventricle and right atrium.
8. This was a single-center experience and limited by a relatively small number of patients with corrected tetralogy of Fallot. The study would have been statistically stronger if more subjects had been evaluated.

Conclusions

The complexity of right atrial dysfunction can be demonstrated by three-dimensional speckle-tracking echocardiography in patients with corrected tetralogy of Fallot.

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Compliance with ethical guidelines

Conflict of interest. A. Nemes, K. Havasi, P. Domsik, A. Kalapos, and T. Forster state that there are no conflicts of interest.

All studies on humans described in the present manuscript were carried out with the approval of the responsible ethics committee and in accordance with national law and the Helsinki Declaration of 1975 (in its current, revised form). Informed consent was obtained from all patients included in studies..

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