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RESEARCH

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CMR parameters and CMR-FT in repaired tetralogy of Fallot

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Abstract

Background: Repaired tetralogy of Fallot patients develops postoperative complications that are in need for follow-up and re-intervention in some circumstances. CMR myocardial feature tracking is a novel method that allows quantification of bi-atrial and bi-ventricular mechanics of deformation. So our aim is to assess the added value of cardiac magnetic resonance imaging and its advanced feature tracking analysis in evaluation of repaired tetralogy of Fallot patients.

Results: CMR was done with feature tracking post-processing analysis for 56 patients with repaired tetralogy of Fallot and 56 healthy volunteers**.** The commonest postoperative complications in patients with repaired tetralogy of Fallot are in the following order: pulmonary regurgitation with subsequent right ventricular dilatation and tricuspid regurgitation followed by pulmonary stenosis, right ventricular dysfunction, right ventricular outflow tract dilatation, left ventricular dysfunction, aortic and mitral regurgitation and residual ventricular septal defect. All right ventricular volumes were found to be significantly increased compared to those of the healthy volunteers (p value < 0.001) also left ventricular end-diastolic and end-systolic volumes indexed were found to be increased in those patients compared to healthy volunteers (p value < 0.001). Right and left ventricular function were significantly lower in those patients compared to controls. Bi-ventricular CMR-FT indices and right atrial global longitudinal strain were found to be significantly lower in patients with repaired tetralogy of Fallot compared to controls. Right atrium global longitudinal strain was found to be significantly correlated with right ventricular global longitudinal strain and did not correlate with right ventricular ejection fraction and end-diastolic volume indexed; p value < 0.001, 0.109 and 0.565, respectively. Right ventricular global circumferential strain was found to be significantly increased in patients with right ventricular outflow tract obstruction compared to those without obstruction (− 16.26 ± 4.27% vs. − 12.2 ± 3.78%, respectively). Pulmonary regurgitant volume indexed was found to be significantly related to right ventricle longitudinal strain (p value 0.027).

Conclusion: Biventricular volumetric measures are increased in patients with repaired tetralogy of Fallot compared to controls; however, feature tracking parameters for both ventricles and right atrium are lower in those patients compared to controls.

Keywords: CMR-FT, rTOF, Cardiac magnetic resonance imaging, Congenital heart disease

Background

Congenital heart disease (CHD) is considered the most common category of birth defects, affecting 1% of population and almost requiring cardiovascular surgery in the first months of life. Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart defect, occurring in about 1 in 3,500 births [1, 2].

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Regarding the embryological background of TOF, Bailliard et al., finally presented the most acceptable explanation for the RVOT obstruction included in TOF, being based on combination of lesions; antero-cephalad deviation of the developing outlet ventricular septum (or failure of its fibrous remnant to muscularize) together with abnormal morphology in the form of hypertrophied septo-parietal trabeculations that encircle the sub-pulmonary outflow tract as well. The four elements of TOF are produced from: (a) this resultant sub-pulmonic obstruction leading to (b) right ventricle hypertrophy, and also (c) mal-aligned ventricular septal defect leading to (d) apparent overriding of the aorta over both ventricles [3].

Without surgical intervention, most patients die during childhood; however, since the introduction of total surgical repair in 1955, the long-term prognosis for these patients has improved, in which the early surgical repair results in 20-year survival rates over 90%. However, on the other hand, all patients require lifelong follow-up to allow identification of the time at which those patients are in need for further surgery or intervention [4, 5].

Various invasive and noninvasive imaging modalities, most commonly echocardiography, cardiovascular magnetic resonance, computed tomography and angiocardiography, provide the imaging information required for diagnosis, management and follow-up in tetralogy of Fallot. Knowledge of the role and protocols of imaging in tetralogy of Fallot is extremely important for the clinical as well as the imaging physician in order to optimize patients' management and long-term prognosis [6].

Approximately 10% of patients with surgically corrected tetralogy of Fallot (TOF) will develop late complications for which they may need re-intervention. Early detection and treatment of postoperative complications and their cardiovascular MR imaging appearances are important to prevent progressive loss of right ventricular function with consequent impairment of exercise capacity and increased risk of fatal arrhythmias [7, 8].

Transthoracic echocardiography is the first line of cardiovascular imaging modality, especially for young infants. However, this method has its limitations including; the poor acoustic window and technical limitations in the evaluation of three-dimensional (3D) right ventricular shape. Therefore, the use of other imaging modalities is mandatory. Cardiac catheterization nowadays is rarely undertaken, except only to estimate right ventricular pressure and to perform interventional procedures [4].

From that, MRI is now recommended as the optimal method in the follow-up of patients with TOF for 1. Quantification of right and left ventricle volumes, mass, stroke volumes and ejection fraction, 2. Evaluation of regional wall motion abnormalities, 3. Imaging the anatomy of the right ventricle outflow tract, pulmonary arteries and aorta, 4. Quantification of atrioventricular and semilunar valve regurgitation, cardiac output and pulmonary-to-systemic flow ratio, 5. Assessment of myocardial viability (LGE), 6. Visualization of coronary artery anatomy [9–11].

One of the recent CMR techniques that has been emerged as a useful tool for the quantitative evaluation of cardiovascular function during the past decade is CMR myocardial feature tracking, this method allows quantification of bi-atrial and bi-ventricular mechanics of deformation; strain, torsion and dyssynchrony [12].

The lack of ideal indices of contractility led the cardiology community to choose EF which is remained the reference standard of ventricular function for decades, despite its inability to assess regional function [12].

This study assesses the added value of CMR in the evaluation of repaired tetralogy of Fallot including the added value of myocardial deformation assessment based on CMR-featuring tracking analysis (Figs. 1, 2, 3, 4).

Methods

A prospective study was carried out on 56 patients with repaired tetralogy of Fallot referred to Diagnostic Radiology and Medical Imaging Department at Tanta University Hospitals and National Heart Institute for cardiac magnetic resonance imaging as well as 56 healthy volunteers. Ethics committee approval and informed consent were obtained.

Inclusion Criteria:

- Patients with tetralogy of Fallot who underwent tetralogy of Fallot repair.

Exclusion Criteria:

- The generally accepted contraindications to perform MRI scan.
- Patients who refuse the examination.
- Patients with bad general condition.

All the patients were dealt with in the following manner:

- Proper fully detailed clinical history taking, including any chronic disease and any previous cardiac intervention.
- Specific history concerning the disease itself, including age at operation, also the patients were asked to bring last echocardiography and renal function tests (for those who were planned to undergo the study with contrast, based on estimated GFR should not be < 30 ml/min/1.73m^2).

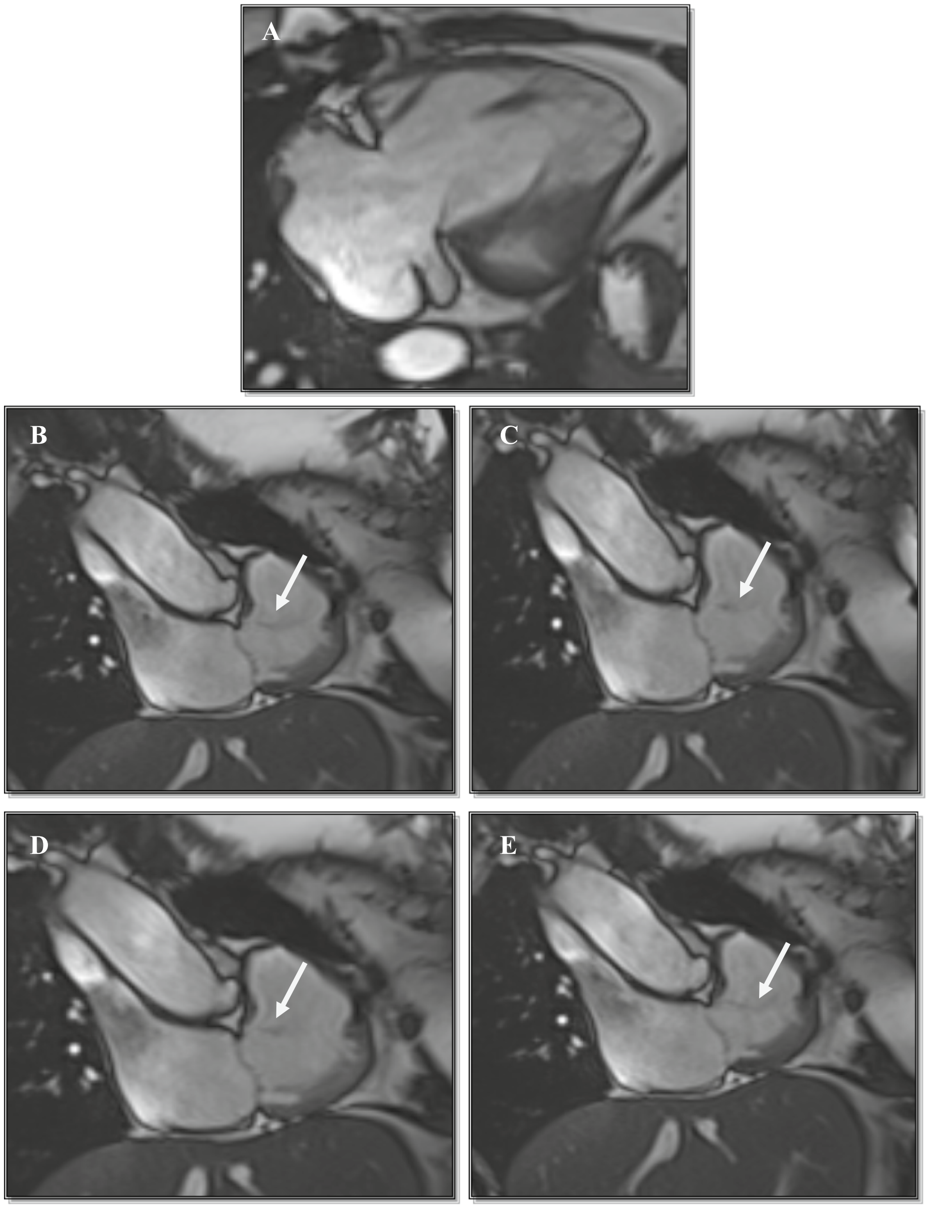

Fig. 1 **A**–**M** CMR revealed: Dilated RV, moderate PS (Venc = 3.5 m/s), mild PR, RF = 17%, mild AR, Qp/Qs = 1.4 denoting residual left → right shunt, dilated RA. A 49-year-old female patient, diagnosed as tetralogy of Fallot, underwent RVOT repair at age of 12-year-old. The patient was referred for RV volumes, function and Qp/Qs quantification. **A** Right 2-chamber cine image at diastole showing dilated, non-hypertrophied right ventricle. **B**, **C**, **D**, **E** Four sequential images right in-flow/ out-flow cine stack showing residual VSD jet. **F** Sagittal pulmonary phase-contrast velocity encoding sequence (in-plane, Venc 1.5 m/s); phase image showing aliasing at the pulmonary valve level requiring increasing the Venc till aliasing disappears. **G** Coronal pulmonary phase-contrast velocity encoding sequence (in-plane, Venc 2 m/s); phase image showing still noted aliasing at the pulmonary valve level requiring increasing the Venc till aliasing disappears. **H**, **I** Coronal pulmonary phase-contrast velocity encoding sequence (in-plane, Venc 3.5 m/s); magnitude and phase images showing disappearance of the aliasing at the pulmonary valve level denoting peak systolic velocity at this level (3.5 m/s) with pressure gradient 49 mmHg calculated by modified Bernoulli equation. **J** Pulmonary phase-contrast velocity encoding sequence (through-plane with Venc 3.5 m/s); phase image showing no aliasing denoting optimum Venc. **K** Phase-contrast velocity encoding sequence (through-plane sub-aortic level with Venc 1.5 m/s); phase image showing regurgitant blood flow for better assessment of regurgitant blood volume and therefore better assessment of regurgitant fraction, in which Qp/Qs can be calculated and found to be equal to 1.4:1 denoting left to right shunt, validating the appearance of residual VSD in the cine images. **L** Sagittal pulmonary cine image at diastole showing dephasing jet of pulmonary regurgitation (PR). **M** Feature-tracking analysis of 4-chamber cine image with endocardial contouring of dilated right atrium, RA GLS (10%) being lower than normal right atrial longitudinal strain range documented in this study (Min–Max = 22.0–54.7%)

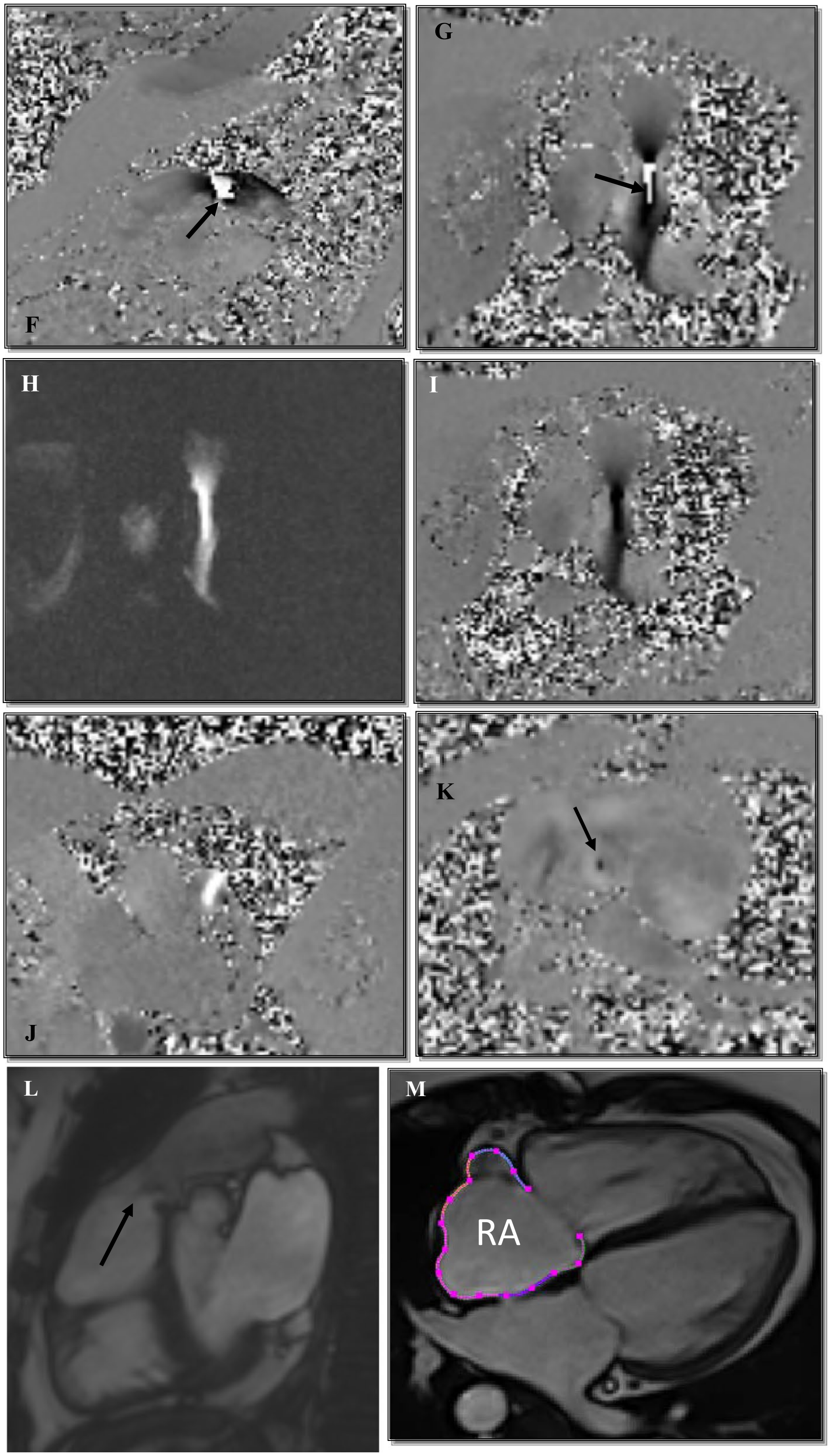

Fig. 1 continued

- More specific history before entering the scanner room about any implanted devices which may be hazardous inside the scanner room or produce image artifact.
- Clinical examination including vital signs monitoring before, during and after MRI examination.
- Weight and height for all patients were measured in order to estimate BSA used in calculating indexed ventricular volumes later on.
- Optimal placement of ECG leads that was very important for gating. The signal should be checked while the patient is outside the scanner bore, inside it and during scanning as well.
- Peripheral intravenous cannula was placed for 34 patients who were decided to have IV gadolinium-based contrast injection (the dose = 0.1 mmol/kg), contrast was needed in one of the following circumstances:

  1. First CMR examination after the correction
  2. Deterioration in clinical status
  3. Deterioration in the ventricular function.

- Proper imaging coil was chosen to maximize S/N ratio over the body portion to be examined, that can be checked by reviewing the localizing images.

Imaging protocol

- *Localizing images (static images)* ECG-gated localizing imaging in the axial, coronal, sagittal and oblique planes, including:

  - Localizer 15 slices, Localizer 60 slices, Localizer false 2 chamber and Localizer false short axis

- *Cine images (dynamic images)* ECG-triggered, breath-hold cine SSFP or free-breathing with increasing averages in the following planes:

  - 4-chamber, LV 2-chamber, 3-chamber, LVOT, RV 2-chamber, RVOT cross, Oblique sagittal parallel to the RVOT and proximal MPA.
  - Ventricular short-axis and axial plane
  - Cine pulmonary sagittal and coronal
  - Sagittal RPA and LPA

- Magnetic resonance angiogram (MRA).
- Flow images (3 combined images; anatomy, magnitude and phase): ECG-triggered, breath-hold through cine phase contrast flow measurements (in plane and through plane) at:
  - MPA, aorta, proximal LPA and RPA.
- *Late gadolinium enhancement (LGE) sequences done for only 34 patients who received GBCA* ECG triggered, breath-hold, performed 10 min after contrast administration, after performing TI scout to detect the proper time of inversion for myocardial nulling including 2, 3, 4-chmaber and short axis as well as phase-sensitive contrast inversion recovery sequences at the same planes.
- The above protocol in a cooperative patient was completed in 65–70 min.

Interpretation:

- Image interpretation was done off-line through full DICOM send/retrieve functionally, network connection with local picture archiving and communication system (PACS), the images and results were reviewed by two readers (two expert radiologists).
- At first, visual assessment was done by viewing localizers and cine images followed by post-processing quantitative assessment.
- Post-processing for flow measurements from phase-contrast sequences (forward, backward, net flow, velocity and regurgitant fraction as well), calculating ventricular volumes and function from short axis + axial cine stack of images, viewing MR angiography on MPR display and late gadolinium enhanced images as well.
- Post-processing was done first for flow analysis as follows:

  - Flow was measured through a specific area in the image by outlining the ROI (region of interest) in each image in the series, all the frames at the sequence should be included in order to obtain flow/cardiac cycle.
  - The results were plotted as flow/time graph, through which forward, backward, net flow could be obtained as well as velocity (that may be slightly underestimated in high velocities) and regurgitant fraction.

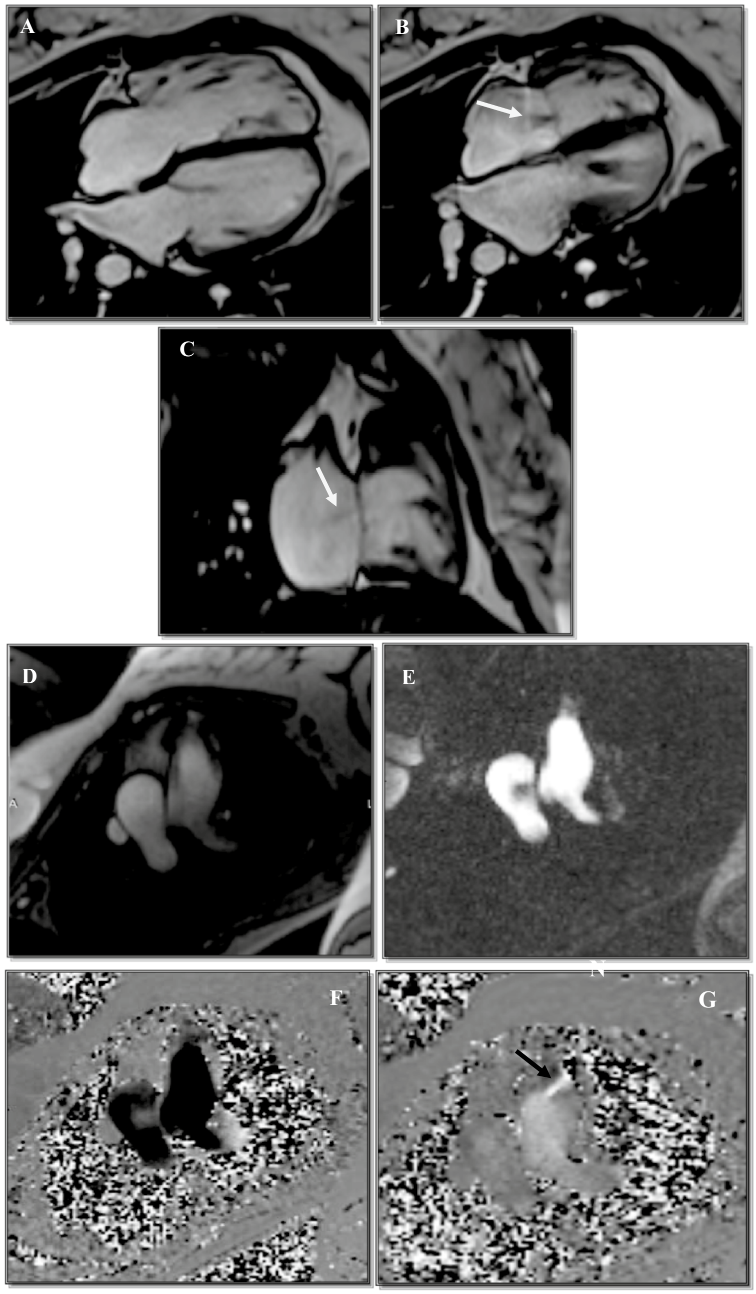

Fig. 2 **A**–**O** CMR revealed: Dilated non-hypertrophied RV, moderate PR, RF = 45%, no PS, moderate TR, RF = 32%, mild AR, RF = 17%, enhancement related to TAP and VSD patch. A 23-year-old female patient, diagnosed as tetralogy of Fallot, underwent trans-annular patch repair at age of 1 year. The patient was referred for baseline CMR study for 1st follow-up. **A** 4-chamber cine images at diastole, **B** at systole and **C** right 2-chamber cine image at systole showing dilated, non-hypertrophied right ventricle at end-diastolic phase and dephasing jet of tricuspid regurgitation during ventricular systole as well. **D**, **E**, **F** Coronal pulmonary phase-contrast velocity encoding sequence (in-plane, Venc 1.5 m/s); anatomy, magnitude and phase images showing no aliasing across denoting no residual stenosis. **G** Coronal pulmonary phase-contrast velocity encoding sequence (in-plane pulmonary with Venc 1.5 m/s); phase image showing dephasing regurgitant pulmonary jet. **H** Phase-contrast velocity encoding sequence at sub-pulmonic level (through-plane, Venc 1.5 m/s); phase image for better assessment of the backward blood volume and consequently better assessment of the regurgitant fraction as well. **I, J** 3-chamber left cine image at diastole and LVOT cine image at diastole showing dephasing jet of aortic regurgitation, regurgitant fraction calculated from the phase-contrast velocity encoding sequence (through-plane at aortic valve), RF = 17%. **K**, **L**, **M** Phase-contrast velocity encoding sequence at sub-aortic level (through-plane, Venc 1.5 m/s); anatomy, magnitude and phase images for better assessment of the backward blood volume and consequently better assessment of the regurgitant fraction as well. **N**, **O** Short axis and 3-chamber late gadolinium enhancement sequences (LGE) showing enhancement at the site of TAP and VSD patch

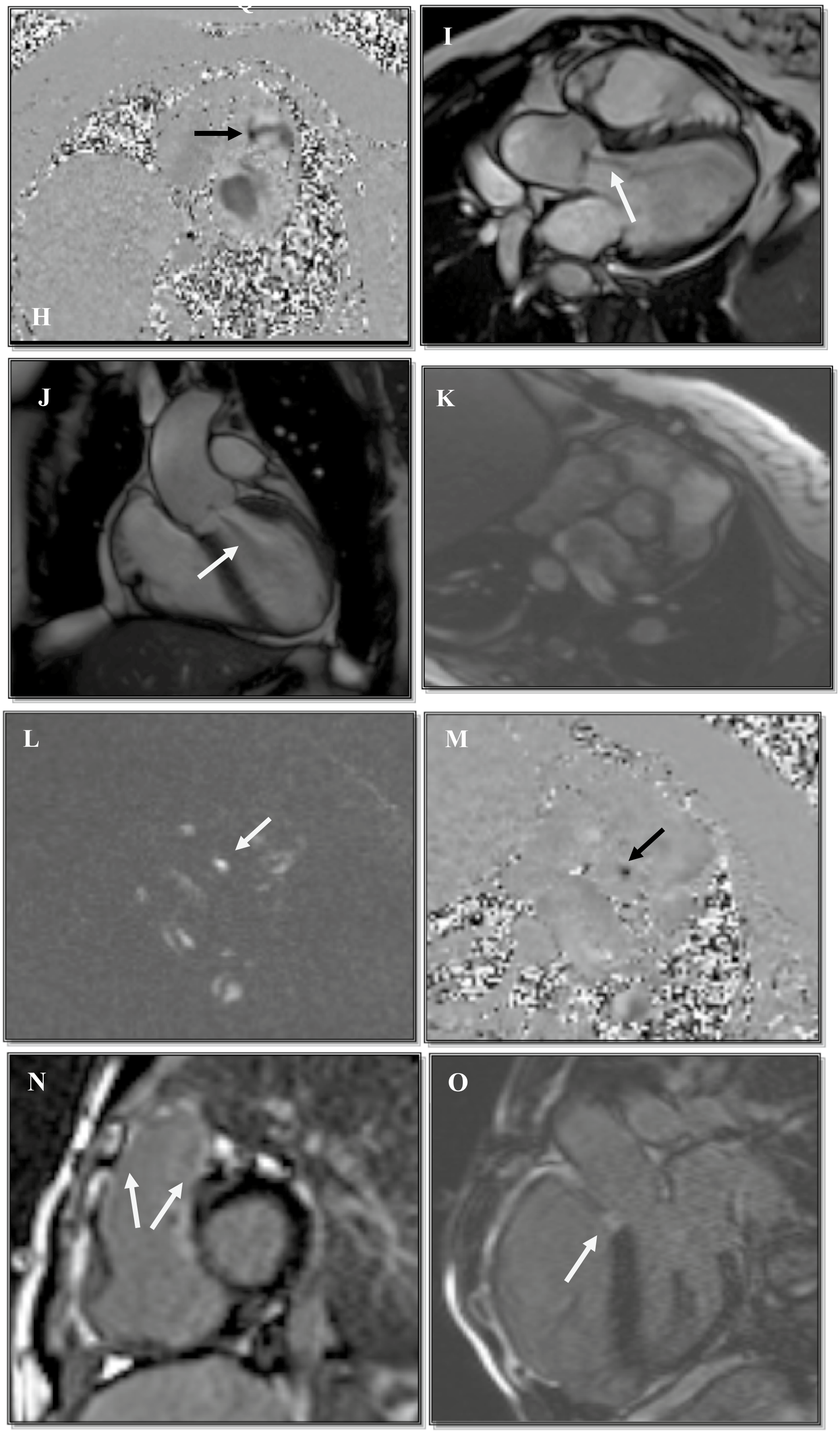

Fig. 2 continued

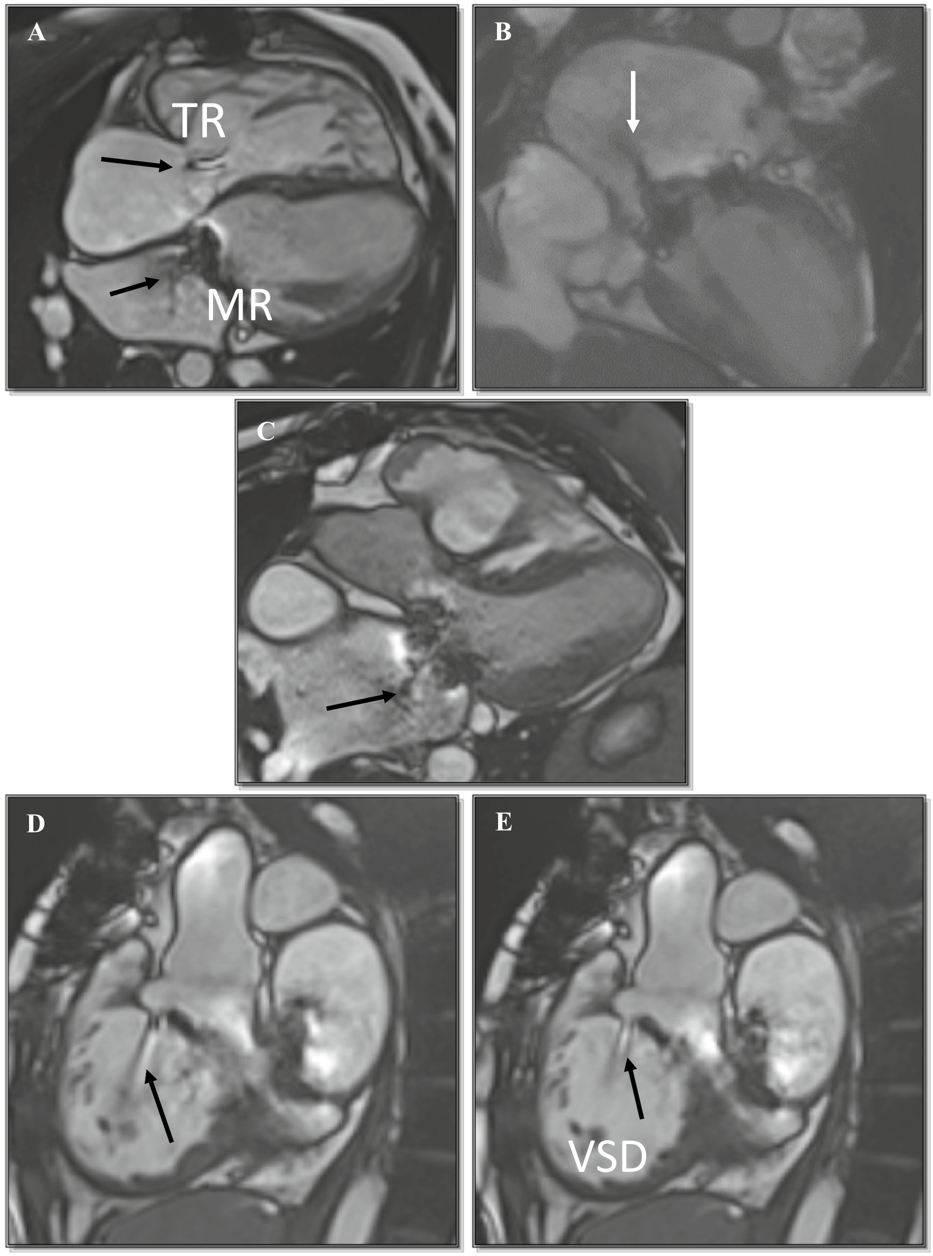

Fig. 3 **A**–**Q** CMR revealed: Dilated RV with fair systolic function, preserved LVEF, moderate PR, RF = 36%, residual PS with maximum velocity = 3.5 m/s, RPA branch stenosis 3 m/s and LPA branch stenosis 2.5 m/s, mild TR, moderate MR, residual VSD with Qp/Qs = 1.5:1. A 23-year-old female patient, diagnosed as tetralogy of Fallot, underwent RVOT repair at age of 1-year-old and mitral valve replacement as well. The patient was referred for RV volumes, function and Qp/Qs quantification. **A**, **B**, **C** 4-chamber cine, left 2-chamber cine and left 3-chamber cine images showing mild tricuspid regurgitation and moderate mitral regurgitation on top of mitral valve replacement. **D**, **E**, **F** Three sequential images from VSD cine showing the systolic jet through the VSD. **G**, **H** Coronal pulmonary cine images during systole showing stenotic jet and during diastole showing dephasing regurgitant jet. **I** Sagittal pulmonary in-plane phase-contrast velocity encoding sequence (phase) showing aliasing across the pulmonary valve at Venc 2.5 m/s needing increasing the Venc for optimal flow assessment. **J**, **K** Coronal pulmonary in-plane phase-contrast velocity encoding sequence (magnitude and phase) showing no aliasing across the pulmonary valve at Venc 3.5 m/s denoting optimal Venc for optimal flow assessment. **L**, **M**, **N**, **O** Sagittal phase-contrast velocity encoding sequences in-plane RPA and LPA (anatomy and phase images) with Venc 2.5 and 2 m/s, respectively, showing aliasing across phase images of both denoting pulmonary branches stenosis and so the need to increase Venc for proper assessment. **P**, **Q** Feature-tracking analysis of short-axis mid-ventricular level and 4-chamber cine in the form of LV endocardial and epicardial contouring as well as RV endocardial contouring, LV circumferential strain (− 12.3%), RV circumferential strain (− 8.6%), radial strain LV (20.2%), LV longitudinal strain (− 14.9%) (4chamber), RV longitudinal strain (− 10.3%), (low feature-tracking RV and LV strain values)

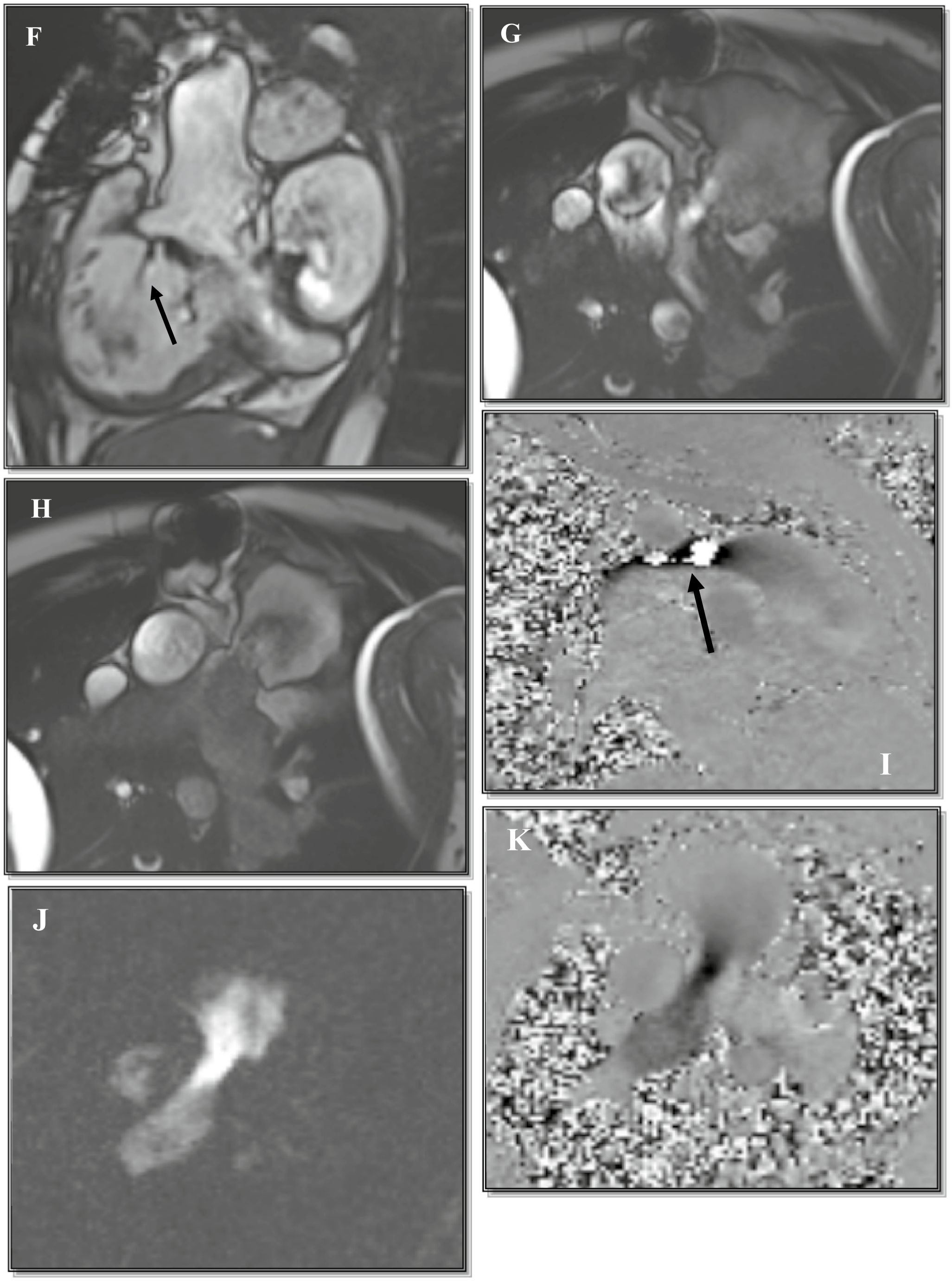

Fig. 3 continued

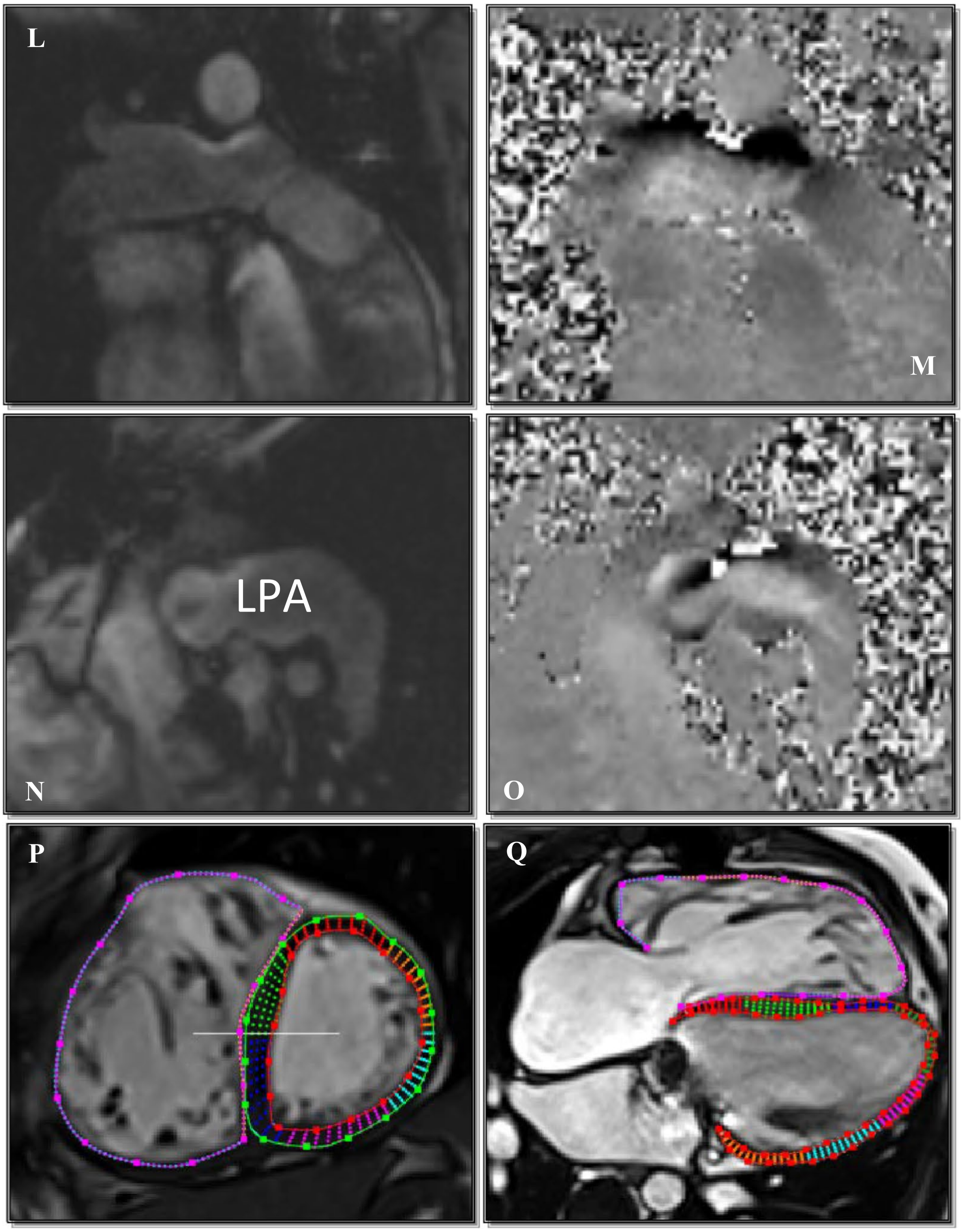

Fig. 3 continued

- Ventriculography:
  - Was done by using the stack of short axis images + axial stack images with computer-semi-automated analysis package.
  - The end-diastolic and end-systolic phases were firstly chosen and that was done for each ventricle individually because of possibilities of having different phase due to conduction affection.
  - ED phase was identified by having the largest LV or RV blood volume and also closure of mitral and tricuspid valves (respectively) would help, or determined as the phase immediately before opening of the aortic valve or pulmonary valve, respectively.

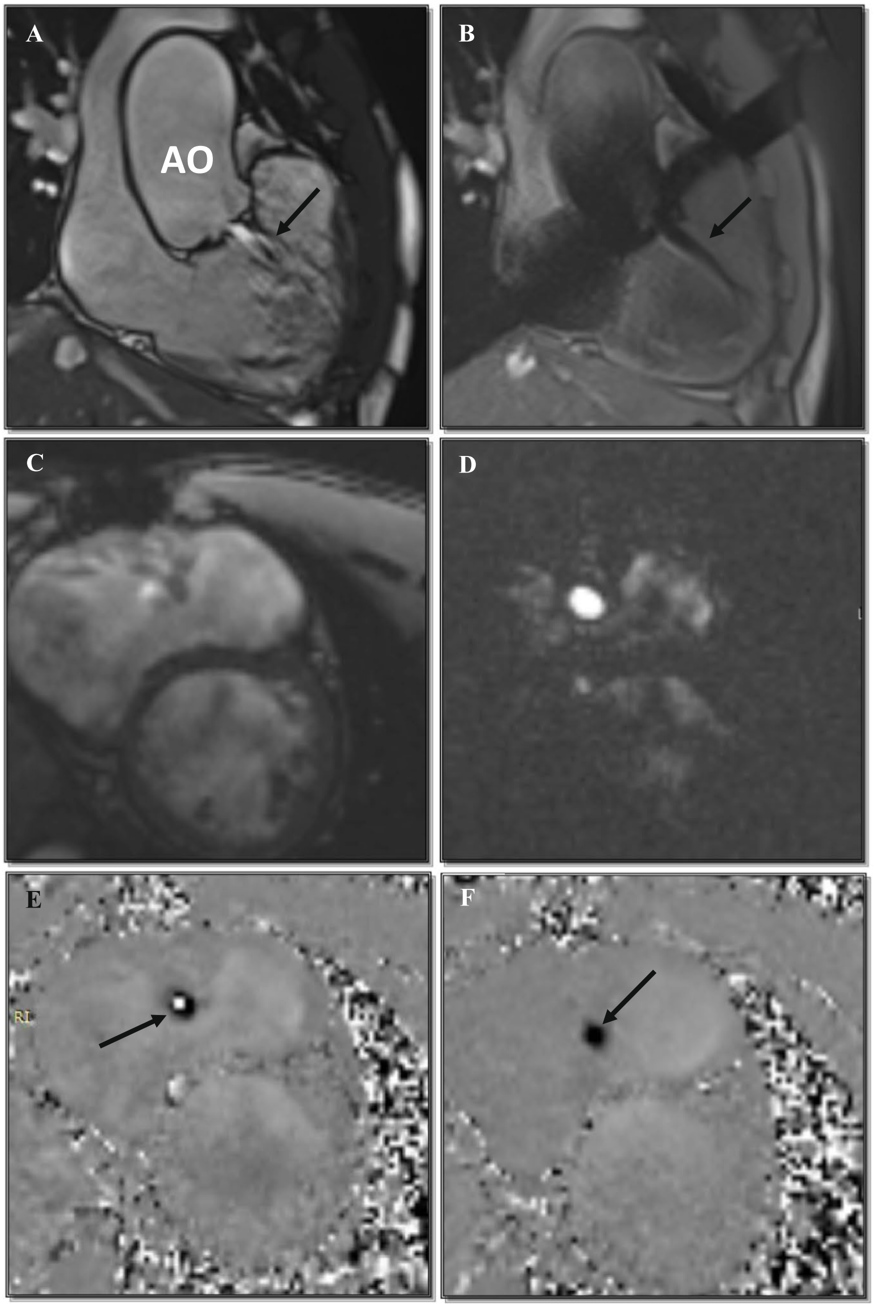

Fig. 4 **A**–**L** CMR revealed: Dilated RV, aortic regurgitation, RF = 5% with dilated aortic root and Asc.Ao, moderate PR, RF = 40%, residual PS, maximum velocity 2.5 m/s, residual VSD (flow across = 59 ml, maximum velocity reached 4.5 m/s) (estimated gradient about 81 mmHg) and Qp/Qs 1.4:1. A 30-year-old male patient, diagnosed as tetralogy of Fallot, underwent RVOT repair at age of 4-year-old. The patient was referred for CMR study for follow-up (RV volumes, function and Qp/Qs quantification). **A**, **B** Right inflow/outflow cine images with and without saturation band showing systolic VSD jet and dilated aortic root. **C**, **D**, **E** Phase-contrast velocity encoding sequence for VSD with Venc 2.5 m/s; anatomy, magnitude and phase images showing aliasing across the VSD at this Venc denoting the need for increasing Venc for proper velocity and flow assessment. **F** Phase-contrast velocity encoding sequence for VSD with Venc 4.5 m/s; phase image showing no aliasing across the VSD denoting optimum velocity. **G**, **H** Sagittal pulmonary phase-contrast velocity encoding sequence (in-plane) at Venc 2 m/s; anatomy and phase showing aliasing denoting need for increasing the Venc for proper velocity and flow assessment. **I**, **J** Sagittal pulmonary phase-contrast velocity encoding sequence (in-plane) at Venc 2 m/s; two images, anatomy and phase showing pulmonary regurgitation during diastole. **K** LVOT cine image showing aortic regurgitant jet during diastole as well as dilated aortic root**.** **L** Axial localizer image showing dilated ascending aorta measured at the level of pulmonary bifurcation measuring about 5.19 × 4.9 cm

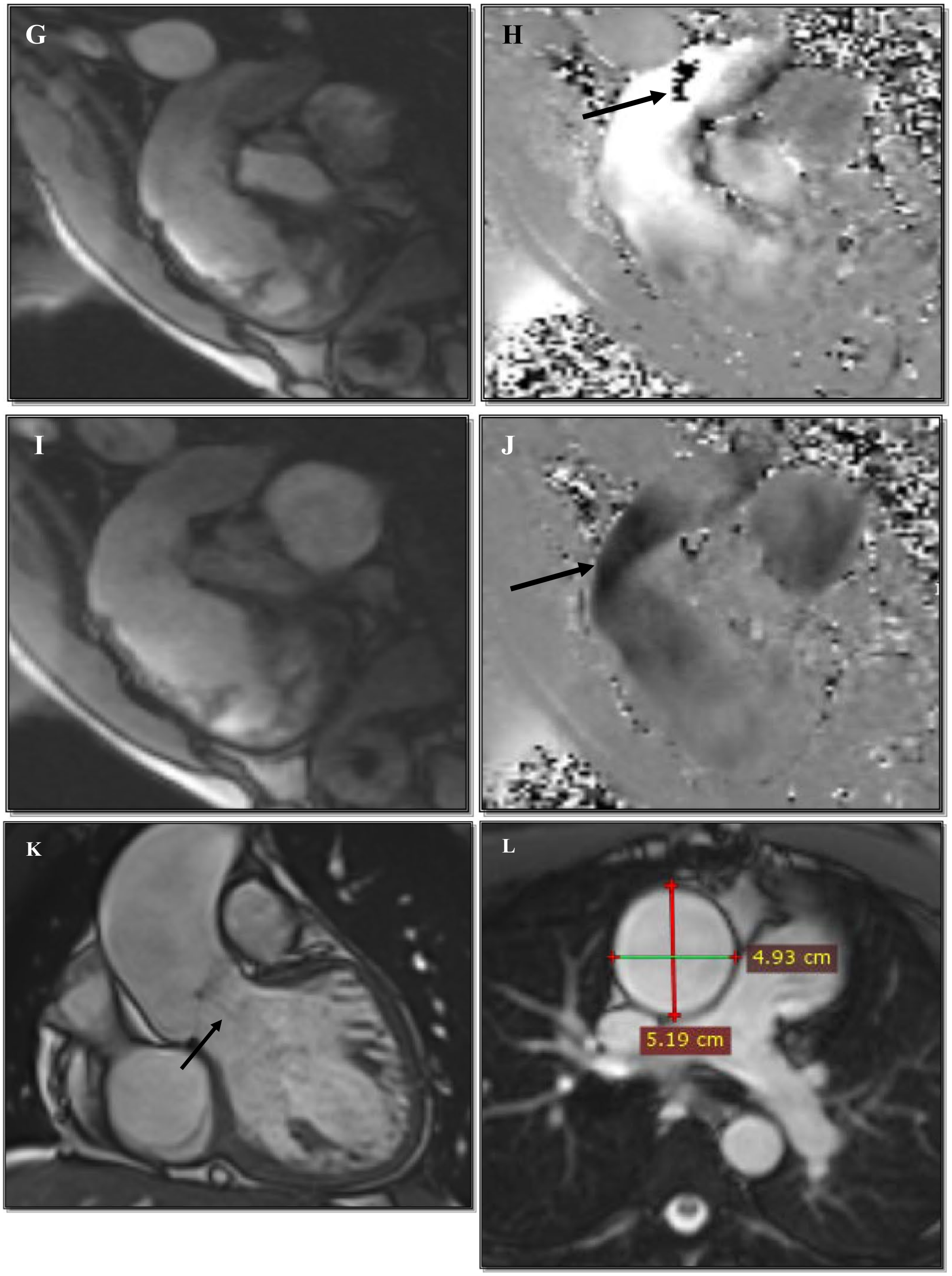

Fig. 4 continued

- ES phase was identified by having the smallest blood volume.
- Drawing the endocardial borders for both ventricles at both previously chosen phases (ED and ES phases) by including the papillary muscles of LV and trabeculations of RV within the blood pool (being time-saving and having no appreciable effect on the ventricular function as being included in both ED and ES phases), also outflow

tracts were included during drawing by the aid of longitudinal axes (being used as reference).

- Confirmation of results:
  - In absence of shunts or valvular regurgitation, RV and LV stroke volumes should be nearly equal.
  - In presence of valvular regurgitation:
    - Aortic and pulmonary regurgitation were calculated directly form the phase-contrast sequence (by subtracting backward flow obtained from the through plane of sub-valvular level from the forward flow obtained from the through plane at the valve level).
    - Mitral regurgitation was calculated indirectly; LV stroke volume minus forward flow in aorta divided by LV stroke volume.
    - Tricuspid regurgitation was calculated indirectly; RV stroke volume minus forward flow in pulmonary artery divided by RV stroke volume.
  - Net pulmonary flow equals to forward RPA flow plus forward LPA flow.
  - In presence of shunts Qp/Qs can be calculated.
- *Magnetic resonance angiogram (MRA)* displayed on MPR for proper assessment of aortic, pulmonary, LPA and RPA measurements.
- Late gadolinium enhanced images:
- Visual assessment was sufficient with no need for further post-processing analysis, in which it was done by comparing LGE images (2, 3, 4 chambers, short axis) with their corresponding cine images.
- Feature tracking strain analysis:
  - In this study, feature tracking strain analysis was carried out for the 56 enrolled patients as well as the 56 healthy volunteers on Segment software version (v3.2 R8531) by using cine short axis as well as cine longitudinal views (2, 3, 4 chamber views).
  - Feature tracing analysis starts by cropping and upsampling the image stack.
  - Circumferential and radial feature tracking strain analysis for LV was done by loading cine short axis, determining the end-diastolic and end-systolic phases, then starting tracking the endocardial and epicardial borders.
  - Longitudinal feature tracking for LV was done by loading cine 2, 3, 4-chambers and defining the endocardial and epicardial borders.
  - For RV feature tracking, the circumferential strain was calculated by tracking the endocardial borders of right ventricle at the short axis cine, longitudinal strain was calculated by tracking RV endocardial borders at 4-chamber view and determining the site of tricuspid valve attachment to the free and septal RV walls.
  - For right atrial feature tracking analysis, the endocardial border of right atrium was tracked at 4-chamber cine with defining the attaching points of tricuspid valve leaflets to RV free and septal walls as done for RV feature tracking analysis.

Statistical analysis of the data

Data were fed to the computer and analyzed using IBM SPSS software package version 20.0. (Armonk, NY: IBM Corp) Qualitative data were described using number and percent. The Kolmogorov–Smirnov test was used to verify the normality of distribution Quantitative data were described using range (minimum and maximum), mean, standard deviation, median and interquartile range (IQR). Significance of the obtained results was judged at the 5% level.

The used tests were

1—Student t test, 2—Mann–Whitney test, 3—Pearson coefficient, 4—Chi-square test, 5—Monte Carlo correction.

Results

In our study, fifty-six patients and fifty-six healthy volunteers were included, in which all patients underwent surgical repair for tetralogy of Fallot. Twenty-six of the rTOF patients were males representing 46.4% and 30 of them were females representing 53.6%, with mean age 19.91 ± 11.25 years. Eighteen of the patients included in this study underwent trans-annular patch repair (32.2%), 33 of them underwent RVOT repair (58.9%), and 5 of them underwent RV-PA conduit repair (8.9%), regarding the healthy volunteers who were recruited in this study, 23 of them were males (representing 41.1%) and 33 of them were females (representing 58.9%) with mean age 21.3 ± 11.57 years.

In this study, the age group (20– < 30) was the most common age group including 16 patients; 6 males and 10 females, followed by age group (40– < 50) including 13 patients; 6 males and 7 females, while the age group (< 10 years old) was the least common one in this study, including 3 patients; 2 males and 1 female (Table 1).

At this study, all the enrolled patients underwent total surgical repair for tetralogy of Fallot, in which three types of operations were done, with mean age at repair

4.41 ± 6.22 years and ranging from < 1 year up to 30 years, RVOT repair was the most common (being done for 33 patients out of 56 representing 58.9%) followed by trans-annular patch repair (done for 18 patients representing 32.2%), and the least number of patients underwent RV-PA conduit (5 patients representing 8.9%).

The timing of surgical repair for those enrolled 56 patients was different, with most of operations (27 of RVOT repair, 10 of trans-annular patch repair and 2 of RV-PA conduit repair) were done before the age of 5 years (Table 2).

At this study, the patients were referred for CMR scan for one indication of those four; either 1. RV volumes, function and quantification of Qp/Qs or 2. for 1st follow-up after the operation or 3. the patient was found to be functionally deteriorated (that was documented by

Table 1 The age and gender of the studied rTOF patients ($n = 56$)

Age group	Number of patients	Percentage (%)	Sex			
			Male		Female	
			No	%	No	%
Age (years)						
< 10	3	5.4	2	3.6	1	1.8
10– < 20	8	14.4	4	7.2	4	7.2
20– < 30	16	28.6	6	10.7	10	17.9
30– < 40	12	21.3	7	12.4	5	8.9
40– < 50	13	23.1	6	10.7	7	12.4
50–60	4	7.2	1	1.8	3	5.4
Total	56	100.0%	26	46.4%	30	53.6%

Table 2 Distribution of the included 56 rTOF patients according to the type of operation done and age at repair

Age at repair (years)	Type of operation						Total	
	RVOT repair		Trans-annular patch repair		RV-PA conduit			
	No	%	No	%	No	%	No	%
< 5	27	48.2	10	17.9	2	3.5	39	69.6
≥ 5	6	10.7	8	14.3	3	5.4	17	30.4
Total	33	58.9%	18	32.2%	5	8.9%	56	100%

Table 3 Relation between contrast and indication of CMR among the studied rTOF patients ($n = 56$)

	Contrast				χ^2	^{MC}p
	No ($n = 22$)		Yes ($n = 34$)			
	No	%	No	%		
Indication						
RV volumes and function	20	90.9	0	0.0	*52.814**	*< 0.001**
1st follow-up	0	0.0	23	67.7		
Deteriorated function	0	0.0	10	29.4		
Deteriorated clinical	2	9.1	1	2.9		

χ^2: Chi-square test, *MC* Monte Carlo

p: *p* value for comparing between different categories

*Statistically significant at $p \leq 0.05$

Italic inidciates statistically significant values recent echocardiography) or 4. The patient was found to be clinically deteriorated (either in the form of arrhythmia detected by ECG or complaining of exercise intolerance or unusual dyspnea).

Twenty patients were referred for quantification of RV volumes, function and Qp/Qs representing 35.6%; however, twenty-three patients were referred for 1st follow-up after surgical repair in order to have base-line for ventricular volumes and function to be used in subsequent follow-up scans representing 41.1%, followed by ten patients were referred upon showing ventricular function deterioration by echocardiography representing 17.9% and the least common (3 patients) were referred for assessment of clinical status deterioration representing 5.4%, the patients referred for RV volumes, function and Qp/Qs quantification were in no need for contrast injection, whereas the patients referred for either (1st follow-up or assessment of deteriorated ventricular function or deteriorated clinical status); being totally 36 in number were all planned to have contrast injection during the scanning; however, CMR (congenital protocol) was done with contrast injection for 34 patients instead of 36 patients as previously planned, as two of the patients referred for clinical status deterioration (presented by arrhythmia), their status interfered with prolongation of scan time and were uncooperative as well, so those two studies were done without contrast injection.

This study revealed statistical significance between the indication for CMR scan and performing the study with contrast, p value < 0.001 (Table 3).

At this study, different echo parameters were assessed including RV dilatation, RV and LV function, residual ventricular septal defect and postoperative valvular complications involving pulmonary regurgitation, residual pulmonary stenosis, tricuspid regurgitation, aortic regurgitation and mitral regurgitation as well.

At this study, the postoperative Fallot complications detected by echocardiography were distributed as follows: 54 patients had RV dilatation (representing 96.4%), 20 patients had RV dysfunction (representing 35.7%), 3 patients had LV dysfunction (representing 5.4%), 50 patients had different degrees of pulmonary regurgitation (representing 89.3%), 38 patients had residual pulmonary stenosis (representing 67.9%), 49 patients had different degrees of tricuspid regurgitation (representing 87.5%), 11 patients had aortic regurgitation (representing 19.6%), 7 patients had mitral regurgitation (representing 12.5%), and 12 patients had residual VSD (representing 21.4%).

As regards to the pulmonary regurgitation, the majority of patients had severe degree of regurgitation (26 patients out of 50 patients with pulmonary regurgitation, representing 46.4% out of the 89.3%).

Table 4 Distribution of the 56 rTOF patients according to different Echo parameters:

Echo parameters		**No**	**%**
RVD	Not dilated (n = 2)	2	3.6
	Dilated (n = 54)		
	Dilated only	44	78.5
	Dilated and hypertrophied	10	17.9
RVEF	Normal	36	64.3
	Impaired	20	35.7
LVEF	Normal	53	94.6
	Impaired	3	5.4
PR	No (n = 6)	6	10.7
	Yes (n = 50)		
	Mild	2	3.6
	Moderate	22	39.3
	Severe	26	46.4
PS	No	18	32.1
	Yes	38	67.9
TR	No (n = 7)	7	12.5
	Yes (n = 49)		
	Trivial	1	1.8
	Mild	25	44.6
	Moderate	18	32.2
	Severe	5	8.9
AR	No (n = 45)	45	80.4
	Yes (n = 11)		
	Trivial	1	1.8
	Mild	9	16
	Moderate	1	1.8
	Severe	0	0.0
VSD	No	44	78.6
	Yes	12	21.4
MR	No (n = 49)	49	87.5
	Yes (n = 7)		
	Trivial	1	1.8
	Mild	4	7.1
	Moderate	2	3.6
	Severe	0	0.0

As regards to the tricuspid regurgitation, the majority of those having tricuspid regurgitation had mild degree (25 patients out of 49 patients, representing 44.6% out of 87.5%).

As regards to aortic regurgitation, residual VSD and mitral regurgitation, the majority of patients enrolled in this study had no aortic regurgitation (45 patients, representing 80.4%), also the majority had no residual VSD (44 patients, representing 78.6%), and the majority had no mitral regurgitation as well (49 patients, representing 87.5%) (Table 4).

Regarding the rTOF complications documented by CMR in this study were RV dilatation, RV and LV dysfunction, residual ventricular septal defect, RVOT dilatation and postoperative valvular complications including pulmonary regurgitation, pulmonary stenosis, tricuspid regurgitation, aortic regurgitation and mitral regurgitation.

At this study, the postoperative Fallot complications detected by CMR were distributed in a descending manner as follows: 54 patients had RV dilatation, pulmonary regurgitation and tricuspid regurgitation as well (representing 96.4% for each), followed by 36 patients had pulmonary stenosis (representing 64.3%), 26 patients had RV dysfunction (representing 46.4%), 19 patients had RVOT dilatation (representing 33.9%), 16 patients had LV dysfunction (representing 28.6%), 13 patients had aortic regurgitation and mitral regurgitation as well (representing 23.2% for each), and 11 patients had residual VSD (representing 19.6%).

As regards to the pulmonary regurgitation, the majority of patients had severe degree of regurgitation (24 patients out of 54 with PR representing 42.8% out of the 96.4%).

As regards to the tricuspid regurgitation, the majority of those having tricuspid regurgitation had mild degree (25 patients out of 54 with PR representing 44.6% out of 96.4%).

As regards to aortic regurgitation, residual VSD and mitral regurgitation, the majority of patients enrolled in this study had no aortic regurgitation (43 patients representing 76.8%), also the majority had no residual VSD (45 patients representing 80.4%) as well as the majority had no mitral regurgitation (43 patients representing 76.8%).

As regards to pulmonary stenosis, 36 patients of those enrolled had PS (representing 64.3%), sixteen of them are associated with branch stenosis (LPA and/or RPA), in which 12 patient had LPA branch stenosis and 12 had RPA branch stenosis and 8 of them had both branch stenoses (Table 5).

This study reported a statistically significant relation between type of operation and postoperative CMR sequel concerning the pulmonary valve complication (either stenosis or regurgitation); in which pulmonary stenosis was significantly related to RVOT repair occurring in 27 patients out of 33 patients underwent this type of operation (representing 81.8%), however occurring in only 6 patients out of 18 patients underwent TAP repair (representing 33.3%), also pulmonary regurgitation was found to be significantly related to TAP repair and RV-PA conduit repair occurring in all patients being repaired by these types of operations, however, occurring in 31 patients out of 33 patients being repaired by RVOT repair (representing 93.9%) (Table 6).

Table 5 Distribution of the studied 56 rTOF patients according to CMR parameters

MRI parameters		**No**	**%**
MRI RVEF	Normal (n = 30)	30	53.6
	Abnormal (n = 26)		
	Fair	16	28.5
	Impaired	10	17.9
RVD	Not dilated (n = 2)	2	3.6
	Dilated (n = 54)		
	Dilated only	41	73.2
	Dilated and hypertrophied	13	23.2
LVEF	Normal (n = 40)	40	71.4
	Abnormal (n = 16)		
	Fair	11	19.7
	Impaired	5	8.9
PR	No (n = 2)	2	3.6
	Yes (n = 54)		
	Trivial	2	3.6
	Mild	5	8.9
	Moderate	23	41.1
	Severe	24	42.8
PS	No	20	35.7
	Yes	36	64.3
TR	No (n = 2)	2	3.6
	Yes (n = 54)		
	Trivial	5	8.9
	Mild	25	44.6
	Moderate	23	41.1
	Severe	1	1.8
AR	No (n = 43)	43	76.8
	Yes (n = 13)		
	Trivial	2	3.6
	Mild	10	17.8
	Moderate	1	1.8
	Severe	0	0.0
MR	No (n = 43)	43	76.8
	Yes (n = 13)		
	Trivial	5	8.9
	Mild	7	12.5
	Moderate	1	1.8
	Severe	0	0.0
VSD	No	45	80.4
	Yes	11	19.6
RVOT dilatation	Not dilated	37	66.1
	Aneurysmally dilated	19	33.9

In this study, regarding the right ventricle, all RV volumes in rTOF patients were found to be significantly increased compared to those of the Hvol (including RVEDV, RVESV, RVEDVI, RVESVI); in which RVEDV and RVEDVI were the most commonly affected followed

Table 6 Relation between type of operation and MRI detected postoperative sequel among the studied 56 rTOF patients

	Type of operation						χ^2	^{MC}p
	Trans annular patch (n = 18)		RVOT repair (n = 33)		RV-PA conduit (n = 5)			
	No	%	No	%	No	%		
RVD								
Not dilated	0	0.0	2	6.1	0	0.0	1.231	0.612
Dilated	18	100.0	31	93.9	5	100.0		
RVEF								
Normal	10	55.6	16	48.5	4	80.0	1.655	0.504
Abnormal	8	44.4	17	51.5	1	20.0		
LVEF								
Normal	13	72.2	23	69.7	4	80.0	0.235	1.000
Abnormal	5	27.8	10	30.3	1	20.0		
PR								
No	0	0.0	2	6.1	0	0.0	9.164*	**0.006***
Yes	18	100.0	31	93.9	5	100.0		
PS								
No	12	66.7	6	18.2	2	40.0	11.793*	**0.002***
Yes	6	33.3	27	81.8	3	60.0		
TR								
No	1	5.6	0	0.0	1	20.0	4.770	0.063
Yes	17	94.4	33	100.0	4	80.0		
AR								
No	14	77.8	26	78.8	3	60.0	1.145	0.713
Yes	4	22.2	7	21.2	2	40.0		
VSD								
No	15	83.3	25	75.8	5	100.0	1.197	0.684
Yes	3	16.7	8	24.2	0	0.0		
MR								
No	14	77.8	27	81.8	2	40.0	3.845	0.116
Yes	4	22.2	6	18.2	3	60.0		

Bold inidciates statistically significant values

by RVESV then RVESVI and RVSV and the least commonly affected was RVSVI, also RV systolic function was found to be significantly decreased compared to that of the Hvol, all indices showed p value ≤ 0.05 (Table 7).

In this study, as regards to the CMR LV indices in rTOF patients, LVEDVI and LVESVI were found to be significantly increased (with the former being more affected) and LV systolic function was found to be significantly decreased compared to Hvol, with p value for each index ≤ 0.05 (Table 8).

Concerning the CMR-FT right and left ventricular parameters, in this study we found that RV global circumferential, longitudinal strain, LV global circumferential, longitudinal and radial strain and RA global longitudinal strain as well were all of abnormal values compared to healthy volunteers.

In which RV GCS and RV GLS were found to be significantly lower in rTOF patients than controls being − 12.66 ± 2.9% versus − 15.8 ± 4.07% and − 19.78 ± 4.97% versus − 22.59 ± 3.55%, respectively. Also LV GCS, LV GLS and LV GRS were significantly lower in rTOF patients compared to controls being − 20.7 ± 4.65% versus − 22.22 ± 2.68%, − 16.92 ± 3.51% versus − 19.35 ± 2.12% and 36.45 ± 8.48% versus 42.97 ± 9.23%, respectively. Moreover, RA GLS was also significantly lower in rTOF patients compared to controls being 14.43 ± 9.09% versus 35.36 ± 7.89%, respectively (Table 9).

In this study when correlating the RV systolic function (RVEF), RVEDVI (being the most commonly affected right ventricular volume), RA longitudinal

Table 7 Comparison between the two studied groups (56 rTOF patients and 56 healthy volunteers) regarding different CMR RV volumetric and function indices

	rTOF patients ($n=56$)	Healthy ($n=56$)	Test of sig	p
MRI RVEF (%)				
Min.–Max	31.0–67.0	48.0–78.0	$t=6.634^*$	<0.001*
Mean ± SD	52.24 ± 8.21	61.43 ± 6.32		
RVEDV (ml)				
Min.–Max	57.0–555.0	74.0–202.0	$t=6.552^*$	<0.001*
Mean ± SD	238.6 ± 114.1	136.52 ± 24.10		
RVESV (ml)				
Min.–Max	30.0–278.0	22.0–94.0	$U=531.500^*$	<0.001*
Mean ± SD	119.9 ± 68.83	53.16 ± 14.99		
RVSV (ml)				
Min.–Max	28.0–277.0	52.0–126.0	$t=5.417^*$	<0.001*
Mean ± SD	121.2 ± 50.40	83.23 ± 14.52		
RVEDVI (ml/m^2)				
Min.–Max	76.0–330.0	50.0–106.0	$t=11.243^*$	<0.001*
Mean ± SD	159.6 ± 54.84	75.20 ± 12.12		
RVESVI (ml/m^2)				
Min.–Max	28.0–165.0	15.0–61.0	$U=136.500^*$	<0.001*
Mean ± SD	77.54 ± 32.61	29.61 ± 8.29		
RVSVI (ml/m^2)				
Min.–Max	46.0–165.0	24.0–89.0	$t=9.199^*$	<0.001*
Mean ± SD	82.28 ± 27.09	46.59 ± 10.45		

SD standard deviation, *t* Student *t* test, *U*: Mann–Whitney test

p: *p* value for comparing between the studied groups

*Statistically significant at $p \leq 0.05$

Table 8 Comparison between the two studied groups (56 rTOF patients and 56 healthy volunteers) regarding different CMR LV volumetric and function indices

	rTOF patients ($n=56$)	Healthy ($n=56$)	Test of sig	p
LVEF (%)				
Min.–Max	36.0–72.0	54.0–77.0	$t=5.342^*$	<0.001*
Mean ± SD	57.0 ± 7.56	63.63 ± 5.38		
LVEDV (ml)				
Min.–Max	29.0–307.0	91.0–189.0	$t=0.248$	0.805
Mean ± SD	135.3 ± 58.79	133.20 ± 22.46		
LVESV (ml)				
Min.–Max	11.0–178.0	29.0–73.0	$U=1322.500$	0.153
Mean ± SD	60.62 ± 34.12	48.66 ± 11.82		
LVSV (ml)				
Min.–Max	18.0–155.0	56.0–121.0	$t=2.463^*$	0.016*
Mean ± SD	74.71 ± 28.80	85.36 ± 14.70		
LVEDVI (ml/m^2)				
Min.–Max	38.0–166.0	25.0–155.0	$t=4.006^*$	<0.001*
Mean ± SD	89.29 ± 24.59	73.43 ± 16.51		
LVESVI (ml/m^2)				
Min.–Max	16.0–87.0	17.0–80.0	$t=4.354^*$	<0.001*
Mean ± SD	39.13 ± 15.05	28.63 ± 9.97		
LVSVI (ml/m^2)				
Min.–Max	20.0–101.0	19.0–62.0	$t=1.730$	0.087
Mean ± SD	49.79 ± 13.26	46.23 ± 7.79		

SD standard deviation, *t* student *t* test, *U* Mann–Whitney test

p: *p* value for comparing between the studied groups

*Statistically significant at $p \leq 0.05$

strain and RV longitudinal strain together, we found that RA GLS correlated with RV GLS and did not correlate with RVEF and RVEDVI as $p<0.001$ regarding the first and >0.05 regarding the other two parameters (p value = 0.109 and 0.565, respectively) (Table 10).

Regarding RVOTO as being an important postoperative residual, the patients could be divided into two groups; with RVOTO representing 32 patients and without RVOTO representing 24 patients, in which there was no statistical significant relation between the two groups concerning RVEF, RVEDVI and RVESVI; however, RV GCS was found to be significantly increased in patients with RVOTO compared to those without RVOTO, with mean − 16.26 ± 4.27% versus − 12.2 ± 3.78%, respectively (Table 11).

In this study, regarding the pulmonary regurgitant volume indexed either ≤ 30 ml/m^2 or > 30 ml/m^2 (in which 30 ml/m^2 being the cutoff value of significant pulmonary regurgitation), showed to be statistically significant related to the RV longitudinal strain with p value 0.027, however no significance between it and RV circumferential strain or LV longitudinal or LV circumferential strain as well (Table 12).

Discussion

Survival of patients with congenital heart disease (CHD) has greatly improved in recent decades, owing to technical advances related to diagnosis and treatment. Many of these patients have had palliative and corrective surgical procedures that make them in continuous need for long-term surveillance by which anatomic parameters can be monitored and complications can be identified on a timely basis [13].

This study was carried out on 56 patients (who were referred for cardiac magnetic resonance imaging for the added value of CMR in postoperative Fallot evaluation by using the conventional congenital CMR protocol in addition to an advanced myocardial deformation analysis done by CMR feature tracking technique), in addition to enrolling 56 healthy volunteers as well to compare the CMR ventricular indices and feature tracking analysis results of those patients to standards gained from these healthy volunteers.

Table 9 Comparison between the two studied groups (56 rTOF patients and 56 healthy volunteers) according to the different CMR FT parameters

	rTOF patients (*n* = 56)	Healthy (*n* = 56)	*t*	*p*
Sax LV GCS %				
Min.–Max	− 29.70 to − 12.0	− 29.60 to − 13.20	2.126*	0.036*
Mean ± SD	**− 20.70 ± 4.65**	**− 22.22 ± 2.68**		
Sax LV GRS %				
Min.–Max	19.70–56.50	22.40–67.20	3.892*	< 0.001*
Mean ± SD	**36.45 ± 8.48**	**42.97 ± 9.23**		
LV GLS %				
Min.–Max	− 23.80 to − 8.70	− 24.60 to − 15.10	*t* = 4.447*	< 0.001*
Mean ± SD	**− 16.92 ± 3.51**	**− 19.35 ± 2.12**		
Sax RV GCS %				
Min.–Max	− 26.30 to − 9.30	− 18.70 to − 7.50	4.712*	< 0.001*
Mean ± SD	**− 12.66 ± 2.90**	**− 15.80 ± 4.07**		
Long axis RV GLS %				
Min.–Max	− 31.30 to − 5.90	− 30.0 to − 15.50	*t* = 3.443*	0.001*
Mean ± SD	**− 19.78 ± 4.97**	**− 22.59 ± 3.55**		
RA GLS %				
Min.–Max	− 12.60–37.60	22.0–54.70	*U* = 73.500*	< 0.001*
Mean ± SD	**14.43 ± 9.09**	**35.36 ± 7.89**		

Bold inidciates statistically significant values

Table 10 Correlation between different conventional and advanced feature tracking right atrial and right ventricular parameters among the studied 56 rTOF patients

		RA GLS	Long axis RV GLS	RVEF	RVEDVI
RA GLS	R	1.000	0.469	0.216	0.079
	P		**< 0.001***	0.109	0.565
Long Axis RV GLS	R		1.000	− 0.202	− 0.047
	P			0.135	0.730
RVEF	R			1.000	− 0.337
	P				0.011*
RVEDVI	R				1.000
	P				

r: Pearson coefficient

*Statistically significant at $p \leq 0.05$

Bold indicates statistically significant values

This study was conducted upon 56 rTOF patients (including 26 males representing 46.4% and 30 females representing 53.6% with mean age 19.91 ± 11.25 years) and 56 healthy volunteers served as controls (including 23 males representing 41.1% and 33 females representing 58.9% with mean age 21.3 ± 11.57), when compared to Kutty et al. [14], who studied 171 patients

Table 11 Comparison between patients with RVOTO and without RVOTO among 56 rTOF patients regarding CMR RV parameters

	With RVOTO (*n* = 32)	Without RVOTO (*n* = 24)	Test of sig	*p*
RVEDVI (ml/m^2)				
Min.–Max	80.0–330.0	76.0–278.0	*t* = 0.245	0.807
Mean ± SD	158.0 ± 61.67	161.67 ± 45.35		
RVESVI(ml/m^2)				
Min.–Max	30.0–165.0	28.0–132.0	*U* = 314.0	0.246
Mean ± SD	75.08 ± 36.03	80.83 ± 27.82		
RVEF (%)				
Min.–Max	41.0–66.0	31.0–67.0	*t* = 1.365	0.178
Mean ± SD	53.53 ± 7.55	50.53 ± 8.89		
Sax RV GCS %				
Min.–Max	− 26.30 to − 9.80	− 22.30 tp − 9.30	*U* = 2.851*	0.021*
Mean ± SD	**− 16.26 ± 4.27**	**− 12.20 ± 3.78**		
Long axis RV GLS %				
Min.–Max	− 28.60 to − 5.90	− 31.30 to − 8.30	*t* = 0.332	0.741
Mean ± SD	− 19.98 ± 4.83	− 19.53 ± 5.26		

SD standard deviation, *t* Student *t* test, *U* Mann–Whitney test

p: *p* value for comparing between With RVOTO and Without RVOTO

Bold indicates statistically significant values

Table 12 Comparison between two groups of pulmonary regurgitant volume (PRV) indexed ≤ 30 and > 30 ml/m^2 among the 56 rTOF patients according to different feature tracking parameters

	PRV (ml/m^2)		*T*	*P*
	≤ 30 (*n* = 32)	> 30 (*n* = 24)		
Sax LV GCS %				
Min.–Max	− 29.70 to − 12.30	− 28.2 to − − 12.0	0.683	0.497
Mean ± SD	− 20.29 ± 4.95	− 21.19 ± 3.96		
Sax RV GCS %				
Min.–Max	− 26.30 to − 9.80	− 23.70 to − 9.30	1.054	0.297
Mean ± SD	− 16.03 ± 4.22	− 14.83 ± 3.62		
Long axis RV GLS %				
Min.–Max	− 31.30 to − 8.30	− 26.60 to − 10.90	2.286	**0.027***
Mean ± SD	− 19.99 ± 4.80	− 22.03 ± 4.04		
LV GLS %				
Min.–Max	− 23.80 to − 9.30	− 21.30 to − 8.70	1.025	0.310
Mean ± SD	− 17.37 ± 3.61	− 16.33 ± 3.50		

SD standard deviation, *t* student *t* test

p: *p* value for comparing between ≤ 30 PRV and > 30 PRV

*Statistically significant at $p \leq 0.05$

Bold indicates statistically significant values with repaired TOF including 94 male patient 55% with age 18.2 ± 8 years together with 140 matched age and gender healthy controls, the two studies are in line to some extent regarding the mean age and gender distribution among the enrolled cohort.

In this current study, the mean age at surgical repair was 4.41 ± 6.22, compared to that reported by Kalaitzidis et al. [15] who reported mean age at repair as 2.4 ± 3.6 years.

Out of the 56 rTOF patients enrolled in this study, 34 patients underwent the study with contrast (representing 60.7%), the indication for contrast in this study is limited to one of these either; 1. to have a baseline for the ventricular volumes and function which will be needed in further follow-up scans or 2. due to deterioration in the clinical status of the patient in the form of recently developed arrhythmia or exercise intolerance or 3. due to deteriorated ventricular function documented by the last echocardiography, otherwise the scan for the remaining 22 patients (39.3%) was done without contrast in order to estimate RV volumes and function and to quantify Qp/Qs as well (in 20 patients of them).

For those 34 patients (60.7%) having CMR scan with contrast, 23 patients of them were referred for 1st follow-up, 10 patients for ventricular function deterioration and 1 of them for clinical status deterioration, and these indications for contrast in CMR congenital protocol were the same discussed by Geva [16].

The 56 rTOF patients at the current study underwent three main tetralogy of Fallot types of repair; RVOT repair, trans-annular patch repair and RV-PA conduit repair, and they were distributed as follows; 33 patients underwent the first type of repair (58.9%), 18 patients underwent the second type of repair (32.2%), and only 5 patients underwent the third type (8.9%); therefore, the RVOT repair had been the most common applied type of repair as regards to this study and the RV-PA conduit repair was the least common, comparing these three techniques of surgical repair in this study and that done in Davlourous et al. [17], that studied 36 patients with repaired TOF; he stated that 19 patients underwent trans-annular patch repair (representing 52.8%), 16 patients underwent RVOT repair (representing 44.5%), and one patient underwent conduit repair (representing 2.8%), so that it is concordant to some extent with this study findings regarding the techniques but at a bit different percentages.

This study mainly assessed the suspected postoperative complications and sequel in repaired tetralogy of Fallot patients and their impact upon ventricular indices and ventricular deformation (calculated by feature tracking strain analysis), and these sequels included pulmonary regurgitation with subsequent RV dilatation, dysfunction and tricuspid regurgitation as well, together with residual pulmonary stenosis and RVOT dilatation or obstruction, LV dysfunction, aortic dilatation and regurgitation, mitral regurgitation and residual VSD.

This study showed these sequels as follows; the most common postoperative sequel was pulmonary regurgitation, RV dilatation and tricuspid regurgitation (in which 54 patients were presented by each sequel representing 96.4% for each) followed by residual pulmonary stenosis (36 patients representing 64.3%), RV dysfunction (26 patients representing 46.4%), RVOT dilatation (19 patients representing 33.9%), LV dysfunction (16 patients representing 28.6%), aortic regurgitation and mitral regurgitation (13 patients representing 23.2% for each) and eventually residual VSD (11 patients representing 19.6%).

Those sequels were the same discussed by Saraya et al. [18], who studied 23 patients with repaired TOF and stated that, the most common sequel was pulmonary stenosis (9 patients representing 39%) then pulmonary regurgitation (7 patients representing 30.4%) followed by RV dysfunction (4 patients representing 17.4%) and finally tricuspid regurgitation (3 patients representing 13.04%).

Saraya et al. [18], reported the pulmonary stenosis as the most common residual complication in patients with repaired TOF with seven patients had LPA branch stenosis (77.8%) and 2 patients had RPA branch stenosis (22.2%); however, in this study sixteen patients were associated with branch stenosis (twelve of them had LPA stenosis and twelve had RPA stenosis with 8 of them having both branch stenoses.

In this study, right ventricular outflow tract obstruction was one of the residual suspected lesions prior to the CMR scan, and out of the 56 patients enrolled in this study, 32 patients had RVOT obstruction (57.1%) and 24 patients had no RVOT obstruction (42.9%) when compared to Latus et al. [19], who studied 54 patients with repaired TOF (nearly the same number as this study), 27 patients had RVOT obstruction and the same number were not having RVOT obstruction (50% for each).

The right and left ventricular indices reported by this study were; RVEF, RVEDV, RVESV, RVSV, RFEDVI, RVESVI, RVSVI, LVEF, LVEDV, LVESV, LVSV, LVEDVI, LVESVI, LVSVI as follows; 52.24 ± 8.21%, 238.6 ± 114.1 ml, 119.9 ± 68.83 ml, 121.2 ± 50.4 ml, 159.6 ± 54.84 ml/m^2, 77.54 ± 32.61 ml/m^2 and

82.28 ± 27.09 ml/m^2 for RV indices, respectively; however, 57 ± 7.56%, 135.3 ± 58.79 ml, 60.62 ± 34.12 ml, 74.71 ± 28.8 ml, 89.29 ± 24.59 ml/m^2, 39.13 ± 15.05 ml/m^2 and 49.79 ± 13.26 ml/m^2 for LV indices, respectively.

Comparing the ventricular indices of this study to different studies published in the literature, significant agreement could be noticed as follows:

Compared to the study of Kalaitzidis et al. [15] regarding mean RVEF, RVEDVI, RVESVI, LVEF, LVEDVI and LVESVI were 52.24 ± 8.21%, 159.6 ± 54.84 ml/m^2, 77.54 ± 32.61 ml/m^2, 57 ± 7.56%, 89.29 ± 24.59 ml/m^2 and 39.13 ± 15.05 ml/m^2 for this study versus 50 ± 9%, 121 ± 33 ml/m^2, 62 ± 24 ml/m^2, 57 ± 9%, 81 ± 17 ml/m^2 and 35 ± 13 ml/m^2, this study is in line with their study regarding these indices.

Also this study is concordant with Gonzalez et al. [20] study regarding the CMR mean ventricular indices, RVEF, RVEDVI, RVESVI, LVEF, LVEDVI and LVESVI were 52.24 ± 8.21%, 159.6 ± 54.84 ml/m^2, 77.54 ± 32.61 ml/m^2, 57 ± 7.56%, 89.29 ± 24.59 ml/m^{2}and 39.13 ± 15.05 ml/m^2 versus 51 ± 8%, 129 ± 40 ml/m^2, 64 ± 25 ml/m^2, 62 ± 9%, 84 ± 16 ml/m^2 and 33 ± 13 ml/m^2, respectively.

Also there is agreement between mean CMR ventricular indices in this study and Ylilato et al. [21], concerning RVEF, RVEDVI, LVEF and LVEDVI being 52.24 ± 8.21%, 159.6 ± 54.84 ml/m^2, 57 ± 7.56% and 89.29 ± 24.59 ml/m^2 versus 54.5 ± 6.5%, 131 ± 23.4 ml/m^2, 58 ± 6.3% and 88.9 ± 12.8 ml/m^2, respectively.

This study also discussed myocardial deformation analysis done by CMR feature tracking technique, being a novel technique that quantitatively calculate the myocardial strain, in which there was no need for additional sequences to be done during the scan (so no added scan time, as it is post-processing technique performed offline based on the basic congenital cines).

Regarding CMR feature tracking results, the parameters obtained were LV circumferential strain (from the short axis cine), LV radial strain (from short axis cine) and longitudinal strain value (from long axis cine 2, 3, 4 chambers), also RV circumferential strain (from short axis cine) and longitudinal strain (form long axis cine: 4 chamber) and right atrial longitudinal strain (from long axis 4 chamber), as these chambers are the mainly affected at repaired tetralogy of Fallot patients.

This study reported mean CMR feature tracking values as follows; LV circumferential strain − 20.7 ± 4.65%, LV radial strain (short axis) 36.45 ± 8.48%, LV longitudinal strain − 16.92 ± 3.51%, RV circumferential strain − 12.66 ± 2.90%, RV longitudinal strain − 19.78 ± 4.97% and right atrium longitudinal strain 14.43 ± 9.09%.

The RA longitudinal strain mean value (14.43 ± 9.09%) in this study at the postoperative Fallot patients is in line with its value reported by Kutty et al. [14] in their study being (13.6 ± 5.7%) who studied 171 patients with repaired tetralogy of Fallot.

Concerning the right and left ventricular myocardial deformation analysis by CMR FT, there is concordance between this study and that of Ylilato et al. [21] concerning right ventricular circumferential strain, RV longitudinal strain, LV circumferential strain and LV longitudinal strain, being − 12.66 ± 2.90%, − 19.78 ± 4.97%, − 20.7 ± 4.65% and − 16.92 ± 3.51% in this study versus − 16.6 ± 3.6%, − 20.6 ± 3.5%, − 18.6 ± 3% and − 15.6 ± 2.9% in their study.

Correlating the advanced CMR indices of myocardial deformation feature tracking and the CMR conventional volumetric and functional indices, this study showed that RA GLS correlated with RV GLS with $p < 0.001$ and r = 0.469 denoting statistical significant directly proportional correlation; however, RA GLS did not correlate with either RVEF or RVEDVI with $p = 0.109$ and 0.565, respectively, these results are in line with those reported by Kutty et al. [14], who documented significant correlation between RA GLS and RV GLS with $p < 0.001$ and r = 0.3 and also no correlation between RA GLS and either RVEDVI and RVEF as well with $p = 0.25$ and 0.47, respectively.

Comparing the RV CMR conventional ventricular volumetric indices, this study found that all RV volumes in rTOF patients were found to be significantly increased compared to those of the Hvol (including RVEDV, RVESV, RVEDVI, RVESVI); also RV systolic function was found to be significantly decreased compared to that of the Hvol and that is concordant with those results of Kempny et al. [22].

Also for LV indices, LVEDVI and LVESVI were found to be significantly increased and LV systolic function was found to be significantly decreased compared to Hvol, however Kempny et al. [22] stated no significant difference between the two groups regarding these left ventricular indices.

As regards to feature tracking parameters, this study stated that RV GCS, RV GLS, LV GCS, LV GLS, LV GRS were significantly lower in rTOF patients compared to controls, comparing this study with that of Kempny et al. [22]; the two studies showed agreement regarding RV GLS, LV GCS, LV GLS, LV GRS; however, this study disagreed with that of Kempny et al., regarding RV GCS in which their study reported that RV GCS was significantly higher in rTOF patients compared to control group and also documented that RVEF was significantly correlated with longitudinal strain but not with circumferential strain, suggesting RV GLS as an early indicator for RV systolic function deterioration.

This study is concordant with Kutty et al. [14] who stated that RV GLS is significantly lower in rTOF than controls being − 12.3 ± 4.2% versus − 18.5 ± 5.3% in Kutty et al. [14], compared to − 19.78 ± 4.97% versus − 22.59 ± 3.55% in this study.

Discordance is found between this study and that of Ylilato et al. [21] regarding RV GCS, in which the latter reported that RV GCS is significantly higher in rTOF patients compared to control group which is against the results of this study, the latter assigned this finding to the compensatory changes that occur in the myocardial function that may be considered as an initial temporary increase in RV strain during childhood.

According to pulmonary regurgitant volume indexed, this study reported 32 patients having PRV ≤ 30 ml/m^2 (57.1%) and 24 patients having PRV > 30 ml/m^2 (42.9%), also PRV indexed was found to be statistically significant with RV GLS with p value 0.027 and nonsignificantly correlated to RV GCS, LV GLS and LV GCS as well, these results are concordant with those of Ylilato et al. [21] who documented that patients with severe pulmonary regurgitant volume (> 30 ml/m^2)showed an enhanced longitudinal strain when compared to patients with milder regurgitation with p value 0.018, being (− 22.03 ± 4.04%) in PRV > 30 ml/m^2 compared to (− 19.9 ± 4.8%) in PRV ≤ 30 ml/m^2 in this study versus (− 22.5 ± 2.9%) and (− 19.7 ± 3.5%) in the other study, respectively.

Concerning the residual RVOT obstruction, this study stated that 32 patients had RVOTO and 24 patients were without RVOTO, in which there was a statistical significance increase of RV GCS in RVOTO group compared to the other group showed no RVOTO that is in line with what Latus et al. [19] had been reported, denoting that residual RVOTO seems to preserve RV strain.

Conclusions

- All bi-ventricular volumetric measures are abnormally increased in rTOF patients compared to controls and also biventricular systolic function is significantly decreased in those patients as well, also feature tracking parameters of both right and left ventricles as well as right atrium including (left ventricle circumferential, radial and longitudinal strain values, right ventricle circumferential and longitudinal strain values and right atrium longitudinal strain) are all significantly lower in rTOF patients compared to control group, moreover higher right ventricular circumferential strain value in patients with RVOTO than those having no RVOTO supporting the need for pulmonary valvular sparing techniques.

Limitations

- This study has some limitations. Firstly, the enrolled healthy volunteers are not age and gender matched with the rTOF patients group. Secondly; small cohort included in this study needed to be increased in order to establish published standard values for CMR-FT to replace ejection fraction as ventricular function indicator in patients with repaired tetralogy of Fallot.

Abbreviations

CMR: Cardiac magnetic resonance; CHD: Congenital heart disease; TOF: Tetralogy of Fallot; RVOTO: Right ventricular outflow tract obstruction; MPA: Main pulmonary artery; LPA: Left pulmonary artery; RPA: Right pulmonary artery; LGE: Late gadolinium enhancement; PRV: Pulmonary regurgitant volume; GCS: Global circumferential strain; GRS: Global radial strain; GLS: Global longitudinal strain; EF: Ejection fraction; PS: Pulmonary stenosis; PR: Pulmonary regurgitation; RA: Right atrium; Asc.Ao: Ascending aorta; CMR-FT: Cardiac magnetic resonance feature tracking; TR: Tricuspid regurgitation; MR: Mitral regurgitation; AR: Aortic regurgitation; TAP: Trans-annular patch; rTOF: Repaired tetralogy of Fallot.

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Author contributions

All authors read and approved the final manuscript for submission. AE and IA suggested the research idea, ensured the original figures and data in the work, minimized the obstacles to the team of work, correlated the study concept and design and had the major role in analysis, RA collected data in all stages of manuscript, and performed data analysis. KE supervised the study with significant contribution to design the methodology, manuscript revision and preparation. IH correlated the clinical data of patient and matched it with the findings, drafted and revised the work. All authors read and approved the final manuscript.

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Availability of data and material

The authors confirm that all data supporting the finding of the study are available within the article and the raw data ad data supporting the findings were generated and available at the corresponding author on request.

Declarations

Ethics approval and consent to participate:

Informed written consents taken from the patients and healthy volunteers, the study was approved by ethical committee of Tanta university hospital, faculty of medicine Committee's reference number: 33265/07/19.

Consent for publication

All participants included in the research gave written consent to publish the data included in the study. Authors accepted to publish the paper.

Competing interests

The authors declare that they have no competing of interests.

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