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CLINICAL RESEARCH

Quality control of cardiac MRI for tetralogy of Fallot: Combination of standard measurements and physiological analysis to detect invalid examinations



Vérification de la qualité des IRM cardiaques pour tétralogie de Fallot : analyse physiologique combinant des mesures standard pour détecter les examens non fiables

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KEYWORDS

Cardiac magnetic resonance imaging;

Summary

Background. – Cardiac magnetic resonance imaging (MRI) is the key examination for patients with tetralogy of Fallot, but it remains challenging. The MRI report should at least mention left (L) and right (R) ventricle end-diastole volumes (V), ejection fraction (EF) and

Abbreviations: CMR, cardiac magnetic resonance; DORV, double outlet right ventricle; MRI, magnetic resonance imaging; NYHA, New York Heart Association; QC, quality control; SD, standard deviation; SSFP, steady-state free precession.

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Quality control;
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reliability;
Tetralogy of Fallot

pulmonary regurgitation (PR). These variables are linked by basic physiology rules and $(V \times EF)_L = (V \times EF)_R(1 - PR)$.

Aims. – To investigate this formula as a quality control of Fallot MRI.

Methods. – A total of 98 consecutive Fallot MRI were included retrospectively. Examinations that failed the formula (with a 10% tolerance) constituted the invalid group and were compared with a control group of the same size. MRIs of both groups were randomly submitted to a senior observer for blinded reassessment. The initial and new reports were compared. The inter-observer limits of agreement were calculated for the different variables within both groups.

Results. – Twelve examinations failed to pass the validation formula. From the 24 reanalysed examinations (12 invalid + 12 controls), four failed to pass the formula (all from the invalid group). Two examinations had significant artefacts in the aorta or pulmonary trunk due to sternal wires. The quality check detected two other patients with atypical anatomy (persistent septal defects), which were not known by the MRI physician and were not detected during the examination. The inter-observer disagreements within the invalid group concerned essentially V_R ($P < 0.02$).

Conclusion. – The quality control detected questionable MRI examinations, in which 83% corresponded to unreliable right ventricle volumes due to questionable manual contours or unreliable output flow due to artefacts.

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MOTS CLÉS

Ciné-IRM cardiaque ;
Test de qualité ;
Artefacts ;
Reproductibilité
inter-observateur ;
Tétralogie de Fallot

Résumé

Contexte. – L'imagerie par résonance magnétique (IRM) cardiaque est devenue l'examen clé des patients avec tétralogie de Fallot mais elle demeure complexe à réaliser. Le compte rendu d'examen devrait mentionner au moins les volumes télé-diastoliques (V) et fractions d'éjection (EF) droite (R) et gauche (L) ainsi que la fraction de régurgitation pulmonaire (PR). Ces variables sont reliées par des règles physiologiques de base : $(V \times EF)_L = (V \times EF)_R(1 - PR)$.

Objectifs. – Investiguer l'intérêt de cette formule comme contrôle qualité des examens IRM de Fallot.

Méthodes. – Un total de 98 IRM cardiaques consécutives pour tétralogies de Fallot ont été rétrospectivement incluses. Le groupe « invalides » a été constitué des examens ne vérifiant pas la formule (avec une tolérance de 10 %) et comparé à un groupe témoin du même effectif. Les examens des deux groupes ont été relus en aveugle par un observateur senior. Les comptes rendus initiaux et finaux ont été comparés. Les limites de concordance inter-observateurs dans les deux groupes ont été calculées pour les différentes variables.

Résultats. – Douze examens ne vérifiaient pas la formule initialement. Parmi les 24 examens (12 invalides + 12 témoins) réanalysés, seulement quatre (tous du groupe invalide) ne vérifiaient toujours pas la formule. Deux d'entre eux correspondaient à des artefacts importants sur les voies d'éjection droite ou gauche dus à des fils sternaux. La formule d'assurance qualité a permis de détecter deux situations anatomiques atypiques (défauts septaux) qui n'étaient pas connues du radiologue ni détectées au cours de l'examen. Les discordances inter-observateurs concernaient essentiellement V_R ($p < 0,02$).

Conclusion. – Le contrôle qualité a permis la détection d'examen IRM douteux, 83 % desquels correspondaient à un volume télé-diastolique discutable du ventricule droit (erreur de contour manuel) ou à une mauvaise évaluation des débits artériels (artéfact de fil sternaux).

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Background

Cardiac magnetic resonance (CMR) is the gold standard for the assessment of pulmonary regurgitation and its effect on the right ventricle [1]. With the improvement of surgical techniques in paediatric patients, the population of adults with congenital heart defects is growing.

Among them, nearly 10% are patients with Tetralogy of Fallot or other similar pathologies with pulmonary valve insufficiency [2]. The American College of Cardiology/American Heart Association guidelines recommend a CMR examination every 2 or 3 years for these patients [3]. Therefore, they constitute an increasing proportion of all magnetic resonance imaging (MRI) examinations. These

CMR examinations can be quite challenging for two reasons:

- the contouring of the dilated right ventricle may be complex [4,5];
- sternal wires and artificial valves (such as the Melody valve) produce artefacts that impair right ventricle contour detection or pulmonary flow measurement.

Moreover, the decision to replace the pulmonary valve is widely based on quantitative measurements provided by CMR. Actual criteria for this intervention include:

- pulmonary regurgitation and tricuspid regurgitation, usually expressed as fractions;
- right and left ventricle end-diastolic volume, usually indexed;
- ejection fraction.

These parameters are linked by basic haemodynamic laws, such as the equality of left and right effective ventricle strokes ($Q_p/Q_s = 1$ in this population). Devos and Kilner [6] proposed the use of haemodynamic laws as quality controls (QCs) to validate CMR results, but not in the case of tetralogy of Fallot. Therefore, we defined the specific QC ratio:

$$\begin{aligned} \text{QC ratio} &= \frac{EF_R \times V_R \times (1 - PR) (1 - TR)}{EF_L \times V_L \times (1 - AR) (1 - MR)} \\ &= \frac{EF_R \times V_R \times (1 - PR)}{EF_L \times V_L} \quad \text{in most cases} \\ &\quad (\text{i.e. when } TR = AR = MR = 0) \end{aligned}$$

where EF_R and EF_L = right and left ventricular ejection fractions; V_R and V_L = right and left ventricle end-diastolic volumes; PR, AR, TR and MR = pulmonary, aortic, tricuspid and mitral regurgitation. EFs and volumes may be expressed in different units, as long as the choice is consistent throughout the equation (ratio or percentage, mL or mL/m²). Regurgitation fraction must be expressed as a ratio (regurgitated volume over total forward volume).

In the theoretical situation where the measurements are strictly unbiased, this QC ratio must be equal to 1. We postulate that each case where it is not equal to 1 (with a 10% tolerance) should be suspected. This study was designed to assess the interest of this specific QC formula on CMR examinations of Fallot patients.

Methods

Population

Every consecutive patient referred to our centre for a CMR examination to assess ventricular volumes and pulmonary regurgitation of a repaired tetralogy of Fallot between October 2008 and March 2014 was included retrospectively. Patients with other 'Fallot-like' congenital heart diseases (pulmonary regurgitation and dilated right ventricle) were also included. Each patient was informed and consented to the use of their data for research purposes. This non-interventional retrospective study complied with the Declaration of Helsinki concerning medical research on human subjects.

CMR image recording

Our CMR protocol for Fallot patients did not change during the period. Studies were performed on a 1.5T GE MRI system (General Electric, Milwaukee, Wisconsin, USA) with subjects in the supine position and using an eight-element cardiac phased-array coil. Localizing scans were initially recorded for determining left ventricle long-axis orientation. A stack of 10–14 contiguous short-axis slices, covering both ventricle volumes, and two perpendicular long-axis views, were recorded using an electrocardiogram-gated balanced steady-state free precession (SSFP) sequence during end-expiratory breath-holds. The main acquisition parameters were as follows: 8 mm slice-thickness, 3.4–4.1 ms repetition time, 1.4–1.7 ms echo time, 45° flip angle, 10–16 k-space lines per segment (depending on breath-holding capacity), 30 phases per cardiac cycle with view sharing, field of view 32–38 cm (depending on the heart size) and 224 × 224 acquisition matrix. When the patients' breath-holding capacities were insufficient, parallel imaging was used, with acceleration factor 2. Phase-contrast cine acquisitions were also recorded with a two-dimensional segmented fast gradient recalled echo using one-directional through-slice interleaved velocity encoding to assess the aortic and pulmonary flows and regurgitations during end-expiratory breath-holds. Typical acquisition parameters were as follows: 8 mm slice-thickness, 7.5–8.2 ms repetition time, 3.1–3.6 ms echo time, 10–15° flip angle, five k-space lines per segment, 30 phases per cardiac cycle with view sharing, field of view 32–38 cm and a 256 × 128 (frequency × phase) matrix. No gadolinium was used.

CMR image post-processing

Ejection fractions and ventricle end-diastole volumes were assessed after manual segmentation of the left and right ventricle endocardium on the set of contiguous short-axis slices with Medis MASS Analysis Plus software package (version 6.0, Medis medical imaging system, Leiden, the Netherlands). Aortic and pulmonary flows and regurgitations were also computed from the phase-contrast cine acquisitions with MR Flow Quantification software (version 3.3, Medis medical imaging system, Leiden, the Netherlands). For this purpose, no image-based velocity offset correction technique was used. Tricuspid and mitral regurgitations were assessed when visible on the SSFP long-axis views as the difference between SSFP-computed and phase-contrast-computed strokes. If no regurgitation was visible in the long-axis cine MRI, mitral and tricuspid regurgitation were presumed to be null.

Constitution of the case and control groups

Two groups of CMR examinations were studied:

- the case group (invalid group) comprised all CMR examinations with a QC ratio outside the range [0.9, 1.1];
- the control group was formed with the same number of examinations arbitrarily chosen among those with a QC ratio inside the range [0.9, 1.1].

Table 1 Main characteristics at the time of CMR (98 CMRs in 69 patients).

	All CMRs (n = 98)	Invalid CMRs (n = 12)	Control CMRs (n = 12)	P ^a
Age at MRI (years)	28 ± 10	32	28	0.44
Weight (kg)	65 ± 16	64	66	0.80
Height (cm)	167 ± 8	167	169	0.63
Initial cardiopathy				0.22
Fallot	93 (94.9)	11 (91.7)	12 (100)	
Pulmonary atresia	2 (2.0)	1 (8.3)	0	
Fallot-like DORV	3 (3.1)	0	0	
Age at surgery (years) ^b	5.4 ± 3	5	5	0.93
RV end-diastolic volume (mL/m ²)	152.5 ± 47	153	151	0.93
RV ejection fraction (%)	47 ± 8	47	48	0.98
LV end-diastolic volume (mL/m ²)	83 ± 15	83	81	0.93
LV ejection fraction (%)	55 ± 6	55	55	1.0
Pulmonary regurgitation (%)	34 ± 17	34	34	0.84
NYHA class I	1 (1.0)	0	0	1.0
NYHA class II	97 (99.0)	12 (100)	12 (100)	1.0
Significant tricuspid regurgitation	8 (8.2)	1 (8.3)	1 (8.3)	1.0

Data are expressed as mean ± SD, mean or number (%). CMR: cardiac magnetic resonance; DORV: double outlet right ventricle; LV: left ventricular; MRI: magnetic resonance imaging; NYHA: New York Heart Association; RV: right ventricular; SD: standard deviation.

^a Statistical tests compare the invalid and control groups using Chi² test, Fisher exact test or Mann-Whitney rank test.

^b Mean ± SD based on 69 patients.

Each CMR examination of both groups was rendered anonymous and submitted a second time, in a random order, to a senior physician experienced in cardiac MRI. The ventricular end-systole and end-diastole volumes were reassessed from the SSFP cine and the ventricular outflow and regurgitations from the phase-contrast acquisitions. The physician was blind to all patient data (including the previous CMR reports) and was forbidden to use the QC formula during the second assessment of volumes and flows.

Statistics

Bland–Altman [7] analyses were performed for each variable (volumes, regurgitation and ejection fractions) in the invalid and control groups to compare the difference between the initial and final assessments of the estimated variable. The differences between the limits of agreement in both groups were tested with the Fisher test for equality of variances. $P \leq 0.05$ was considered to be statistically significant. Statistics were performed with R (version 3.0.2013-5-12, R Foundation for Statistical Computing, Vienna, Austria) [8]. The uniform random function ‘runif’ was used to select the controls.

Analysis of the cases failing the test twice

Each examination of both groups was retested with the QC formula using the new (reassessed) volumes and flow measurements. Each case in the invalid group that still did not fulfil the formula after reassessment of volumes and flow was carefully analysed to understand the cause of the abnormality. Medical records were consulted when available for this purpose.

Results

A total of 98 CMR examinations performed in our centre for assessment of a pulmonary regurgitation were identified in our database. These CMR examinations corresponded to a total of 69 patients (14 patients had undergone two MRIs, five had undergone three MRIs and one had undergone four MRIs during the inclusion period). Of these, 65 patients had a corrected tetralogy of Fallot, two had a pulmonary regurgitation after neonatal pulmonary valvulotomy (one performed in 1981 for an isolated neonatal stenosis and one for a pulmonary atresia without ventricular septal defect) and two had a ‘near-Fallot’ double outlet right ventricle (DORV). The main characteristics at the time of the CMR are summarized in Table 1.

The QC ratio was successfully computed for all examinations. Twelve examinations (from 10 patients) did not comply with the QC formula (QC ratio \notin [0.9, 1.1]) and constituted the invalid group. The control group was made up of 12 examinations arbitrarily selected from the 86 remaining examinations for which QC ratio \notin [0.9, 1.1] (Fig. 1). These 24 examinations were reassessed by an independent senior physician.

The Bland–Altman analyses for the 24 reassessed patients are presented in Table 2 and on Figs. 2 and 3. The largest differences between both measurements were for the right ventricle volume (limits of agreement 38.3 ± 9.8 mL/m² in the invalid group versus 18.9 ± 4.8 mL/m² in the valid group; $P = 0.013$). The other variables were not significantly different between the two assessments. After reassessment, 20 examinations complied with the QC ratio formula and four examinations of the invalid group still did not comply with the QC ratio formula (Fig. 1).

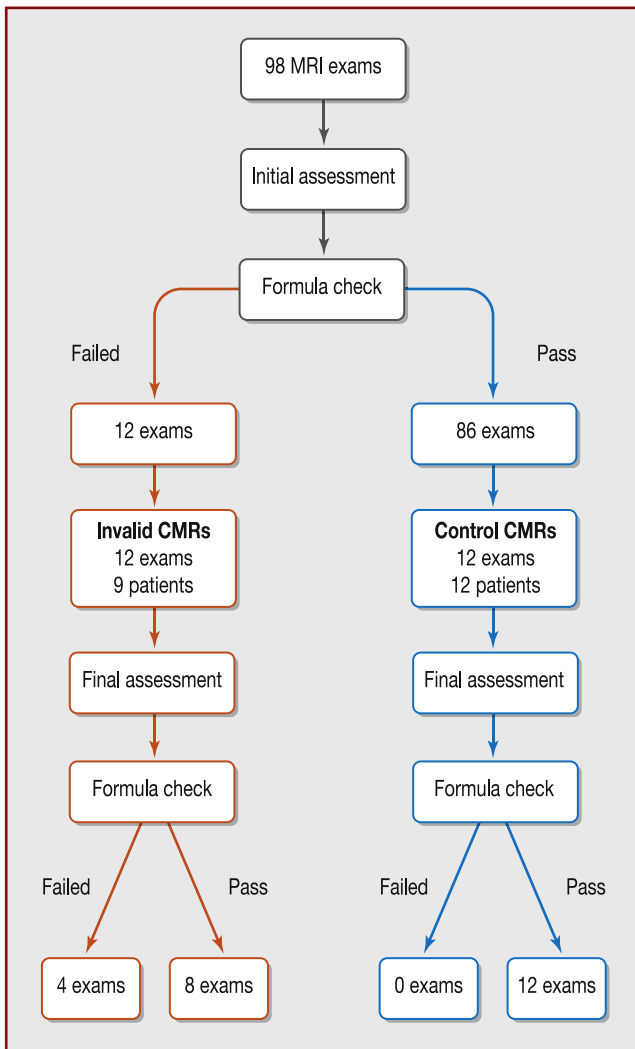


Figure 1. Flow chart of the study. After reassessment of volumes and flows, four studies remained ‘invalid’. CMR: cardiac magnetic resonance.

The medical files and complete MRI examinations of the four examinations failing to pass the formula were analysed. Patient 1 was a 39-year-old repaired Fallot adult with a significant residual ventricular septal defect. The defect was not visible in the cine acquisitions but could have been hypothesized because of a small but distinct flow artefact visible in at least one SSFP short-axis slice (Fig. 4A). This

was recently confirmed by the surgeon during pulmonary reevaluation with pulmonary homograft. Patient 2 had a significant right-to-left shunt through an atrioseptal defect in the ostium secundum position. The shunt was not clearly visible in the cine acquisitions (no displacement artefact). However, the horizontal long-axis view was mispositioned, maybe because of a very large coronary sinus (associated with a left superior vena cava) that could have misled the radiographer. Patients 3 and 4 had artefacts in the aorta or pulmonary artery due to sternal wires. These artefacts resulted in a reduction of the computed flow and therefore in a wrong Q_p/Q_s (1.1 and 0.69, respectively). The aortic artefact (patient 3) constituted a dark disc centred on the wire (Fig. 4B). This disc partially cancelled the aortic signal and thus resulted in higher Q_p/Q_s . The pulmonary artefact (patient 4) was more unusual and consisted of a dark bi-lobular spot ($10 \times 5 \text{ mm}^2$) projected in the pulmonary trunk in the location of the ejection vortex during systole (Fig. 4C).

Discussion

We have shown that the use of a simple QC validation formula was very useful in our retrospective population to detect technical or medical issues concerning patients assessed by cardiac MRI for pulmonary regurgitation. In our population, 12% of the examinations would have been detected by our QC formula if it had been used in a systematic manner.

For eight of the detected CMR examinations, the second contouring of the ventricles gave results that complied with the QC formula. The Bland–Altman analyses of the initial and final assessments show that the only significant difference between both assessments concerned the right ventricle volumes. This implies that the eight corresponding QC failures were very probably due to unreliable contouring of the right ventricle endocardium. This result was expected, as it has been proven that the contouring of the right ventricle suffers from high variability [4,5]. In the control group, the limits of agreement for the end-diastole right ventricle indexed volume was 18.9 mL/m^2 , which is very close to published data concerning the same kind of population [4]. This value is quite important when compared to the mean end-diastole right ventricle indexed volume in the control population (151 mL/m^2) and the ratio $18/151$ is higher than the tolerance limit of 10% that we accepted for our QC formula. This formula could be a great tool to

Table 2 Limits of agreement between the two assessments.

	Invalid CMRs (n = 12)	Control CMRs (n = 12)	P
LV end-diastolic volume (mL/m^2)	13.2 ± 3.3	13.3 ± 3.4	0.99
LV ejection fraction (%)	4.7 ± 1.3	6.2 ± 1.6	0.40
RV end-diastole volume (mL/m^2)	38.3 ± 9.8	18.9 ± 4.8	0.013
RV ejection fraction (%)	8.7 ± 2.2	7.8 ± 2.0	0.70
Pulmonary regurgitation (%)	3.7 ± 0.9	3.1 ± 0.8	0.55

Data are presented as limit of agreement \pm SD. CMR: cardiac magnetic resonance; LV: left ventricular; RV: right ventricular; SD: standard deviation.

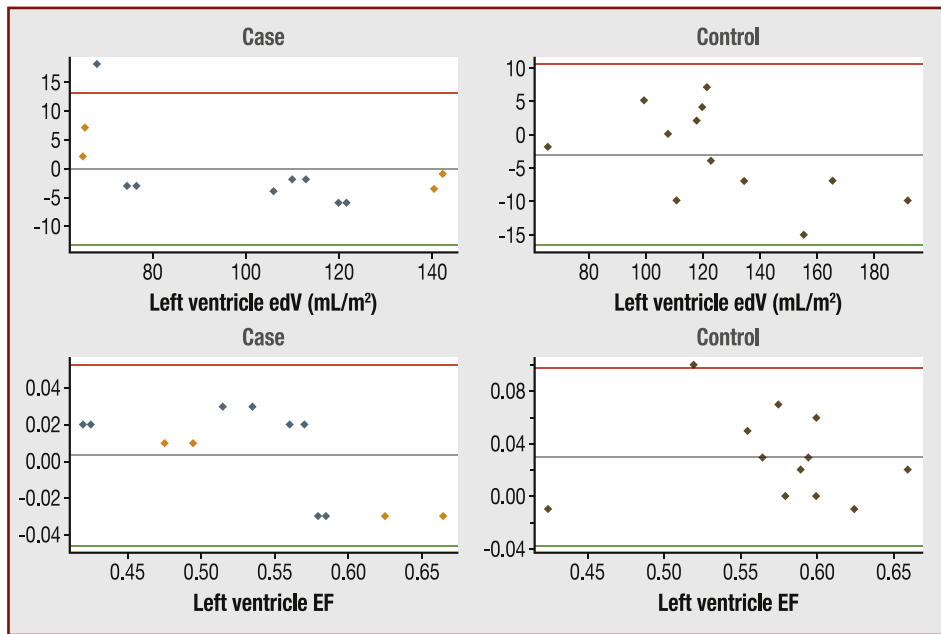


Figure 2. Bland–Altman plots of the end-diastole volumes (edV) and ejection fractions (EF) of the left ventricle. The colored dots correspond to examinations performed twice on the same patients (at different times). The x axes are means of the two readings while the y axes are the differences.

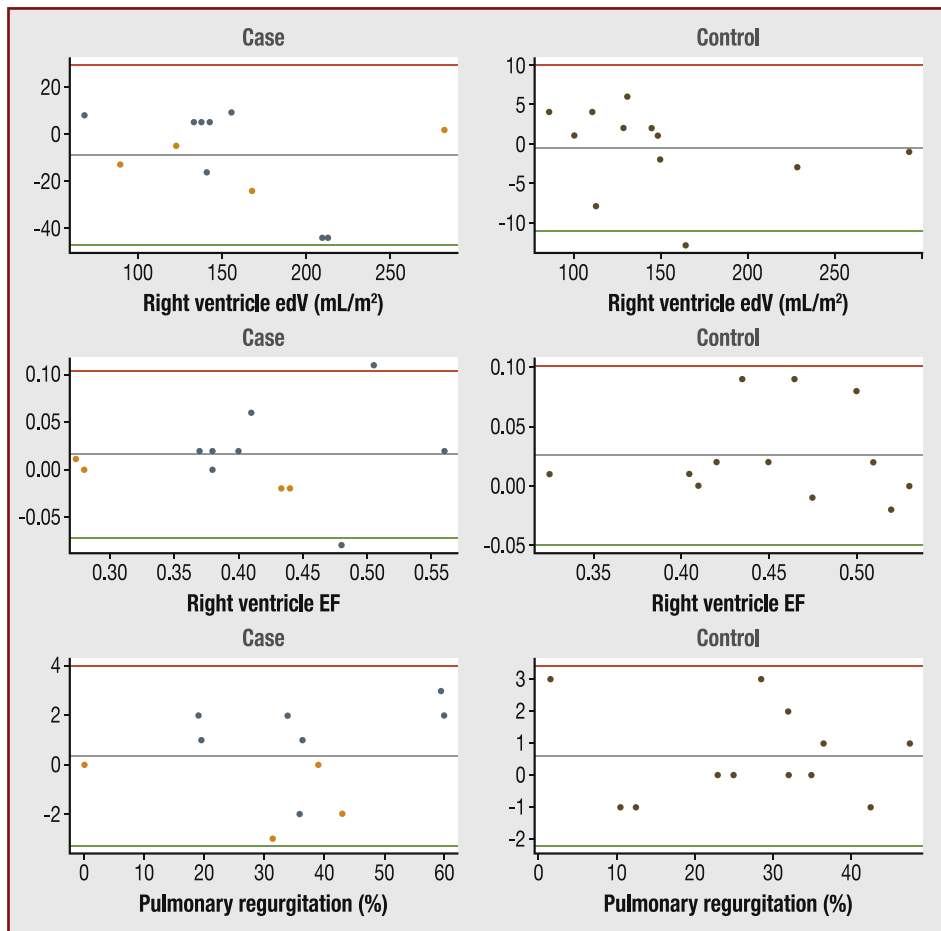


Figure 3. Bland–Altman plots of the end-diastole volumes (edV) and ejection fractions (EF) of the right ventricle and of the pulmonary regurgitation. The colored dots correspond to examinations performed twice on the same patients (at different times).

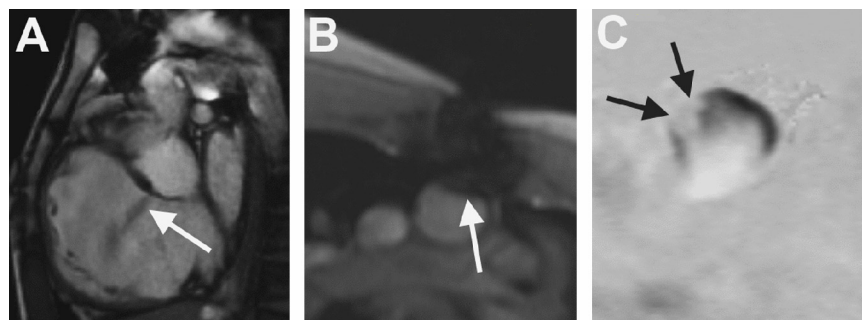


Figure 4. Examples of the situations detected by the quality control (QC) formula. A. Persistent ventricular septal defect causing a flow artefact (white arrow). B. Metallic artefact in the aorta (white arrow). C. Metallic artefact in the pulmonary trunk (black arrow).

detect CMR examinations with unreliable right ventricle contours. We advocate that in a clinical situation, when a CMR examination fails to pass the QC, the MRI physician should check the endocardial contours that were traced. Indeed, in our population, the eight detected examinations would have benefited from this alert signal with a better contouring of the right ventricle.

Four cases were also detected by our QC ratio formula with no apparently anomaly during the right ventricle contouring. The four cases had unexpected Q_p/Q_s ratios. Two of them were due to acquisition artefacts during the phase-contrast sequences. Sternal wire creates void in the signal and the artefact can normally be easily detected as black shapes in the magnitude images or null velocity shapes (grey) in the phase-contrast images. In patient 3, the artefact (white arrow on Fig. 4B) was correctly identified and mentioned in both reports. We had no way, in this retrospective study, to know how the first MRI physician performed his analysis. However, the second MRI physician recognized that he had been influenced by the aortic flow and used this information to adapt the left ventricle contours, resulting in a slightly reduced left ventricle end-diastolic volume. In patient 4, the artefact (black arrows on Fig. 4C) was not mentioned by the MRI physicians. It was indeed located in an unusual position in the pulmonary trunk. The second MRI physician was aware that this CMR study contained abnormal results but could not identify where the mistake was. He recognized that he may have been influenced by the computed Q_p and may have somehow adapted the contouring of the right ventricle. Eventually, the ventricle volumes were probably incorrectly underestimated. It may be conjectured that the artefact also led to a wrong computation of pulmonary regurgitation. Firstly, pulmonary regurgitation was very high for this case (59%). Secondly, the signal void was positioned just at the place where the ejection vortex appears during systole, whereas the regurgitation flow had no such vortex and occupied the entire pulmonary trunk. Therefore, the forward component of the flow was more affected by the void artefact than the backward component of the flow. This hypothesis is not proven, however. Anyhow, the presence of a void artefact should always be checked by the MRI physician, especially if the QC ratio formula remains invalid even after right ventricle volume reassessment.

Patients 1 and 2 had intracardiac shunts that were not visible in the cine MRI sequences. The MRI physicians should

bear in mind the possibility of atypical anatomy when the computed Q_p/Q_s is far from 1 with no visible artefact in the phase-contrast sequences. Tetralogy of Fallot with septal defect usually results in an increased Q_p/Q_s , in situations of atrial septal defect with low right atrial pressure or in situations of ventricular septal defect. However, it can also result in a decreased Q_p/Q_s , in situations of atrial septal defect with high right atrial pressure due to right ventricle dysfunction. The measured ratio Q_p/Q_s is also abnormally low in situations of aortopulmonary collaterals. Our data prove that these anomalies may be very difficult to detect during post processing; rather, they need to be looked with specific acquisitions. Indeed, looking for the medical records of the patient before writing the CMR report would be very time consuming in a clinical situation. Therefore, these last two examinations would probably have been left unexplained, but at least the MRI physician would have been able to mention in his report that there were some inconsistencies in the examinations. This would have resulted in a significant improvement of the quality of the CMR results with only a small increase in the workload.

Other imaging modalities, such as 3D echography, have presented limitations to assess the volume of dilated ventricles [9]. Quality checking was one answer proposed to cope with those limitations [10, 11]. To our knowledge, there is currently no official recommendation from cardiology or MRI societies for QC of quantification during cardiac MRI [12–14]. We advocate the use of the QC ratio defined in this paper. When a given CMR study fails to fulfil the formula, MRI physicians should check the right ventricle contouring and, in situations of abnormal Q_p/Q_s , should also check the absence of artefacts in the great vessels. Eventually, the MRI physician should mention in his report that there may be some inconsistency in the study or that a septal defect should be suspected.

Limitations

This study was designed and conducted with the sole purpose of testing – in our centre – the usefulness of a quality check to improve MRI assessment of ventricle volumes, ejection fraction and regurgitations. Other information may be obtained during an MRI examination (e.g. size of the pulmonary arteries, size of the right ventricular outflow tract) that were not considered in this study.

Conclusions

This retrospective study showed that the use of the proposed QC ratio formula could improve the quality of the CMR reports of patients addressed for pulmonary regurgitation. In our centre, it would have prevented unreliable right ventricle contours (8% of the population) and detected four difficult cases with either impaired flow analysis or atypical anatomy.

Disclosure of interest

The authors declare that they have no competing interest.

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References

- [1] Hundley WG, Bluemke DA, Finn JP, et al. ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance: a report of the American College of Cardiology Foundation Task Force on expert consensus documents. *Circulation* 2010;121:2462–508.
- [2] Baumgartner H, Bonhoeffer P, De Groot NM, et al. ESC guidelines for the management of grown-up congenital heart disease (new version 2010). *Eur Heart J* 2010;31:2915–57.
- [3] Warnes CA, Williams RG, Bashore TM, et al. ACC/AHA 2008 guidelines for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association Task Force on practice guidelines (Writing Committee to Develop Guidelines on the Management of Adults With Congenital Heart Disease). Developed in collaboration with the American Society of Echocardiography, Heart Rhythm Society, International Society for Adult Congenital Heart Disease, Society for Cardiovascular Angiography and Interventions, and Society of Thoracic Surgeons. *J Am Coll Cardiol* 2008;52:e143–263.
- [4] Bonnemains L, Mandry D, Marie PY, Micard E, Chen B, Vuissoz PA. Assessment of right ventricle volumes and function by cardiac MRI: quantification of the regional and global inter-observer variability. *Magn Reson Med* 2012;67:1740–6.
- [5] Bonnemains L, Mandry D, Menini A, et al. Surface-length index: a novel index for rapid detection of right ventricles with abnormal ejection fraction using cardiac MRI. *Eur Radiol* 2013;23:2383–91.
- [6] Devos DG, Kilner PJ. Calculations of cardiovascular shunts and regurgitation using magnetic resonance ventricular volume and aortic and pulmonary flow measurements. *Eur Radiol* 2010;20:410–21.
- [7] Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–10.
- [8] R Development Core Team. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2009.
- [9] Selly JB, Iriart X, Roubertie F, et al. Multivariable assessment of the right ventricle by echocardiography in patients with repaired tetralogy of Fallot undergoing pulmonary valve replacement: a comparative study with magnetic resonance imaging. *Arch Cardiovasc Dis* 2015;108:5–15.
- [10] Dvorak RA, Brown RK, Corbett JR. Interpretation of SPECT/CT myocardial perfusion images: common artifacts and quality control techniques. *Radiographics* 2011;31:2041–57.
- [11] Wong M, Staszewsky L, Volpi A, Latini R, Barlera S, Hoglund C. Quality assessment and quality control of echocardiographic performance in a large multicenter international study: Val-sartan in heart failure trial (Val-HeFT). *J Am Soc Echocardiogr* 2002;15:293–301.
- [12] Klinke V, Muzzarelli S, Lauriers N, et al. Quality assessment of cardiovascular magnetic resonance in the setting of the European CMR registry: description and validation of standardized criteria. *J Cardiovasc Magn Reson* 2013;15:55.
- [13] Douglas P, Iskandrian AE, Krumholz HM, et al. Achieving quality in cardiovascular imaging: proceedings from the American College of Cardiology – Duke University Medical Center Think Tank on Quality in Cardiovascular Imaging. *J Am Coll Cardiol* 2006;48:2141–51.
- [14] Douglas PS, Chen J, Gillam L, et al. Achieving Quality in Cardiovascular Imaging II: proceedings from the Second American College of Cardiology – Duke University Medical Center Think Tank on Quality in Cardiovascular Imaging. *JACC Cardiovasc Imaging* 2009;2:231–40.