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Review

Advanced Imaging Technologies for Assessing Tetralogy of Fallot: Insights Into Flow Dynamics

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ABSTRACT

Tetralogy of Fallot is the most common cyanotic congenital heart defect requiring surgical repair. Although surgical interventions have significantly reduced mortality, postrepair complications, such as pulmonary valve regurgitation and stenosis, may lead to adverse outcomes, including right ventricular dysfunction and increased risks of morbidity and mortality. This review explores the potential of advanced imaging technologies, including 4-dimensional–flow magnetic resonance imaging and high-frame-rate echocardiography, in providing valuable insights into blood flow dynamics and energy parameters. Quantitative measures, such as energy loss and vorticity, along with qualitative flow analysis, can provide additional insights into adverse haemodynamics at a potentially earlier and more reversible stage. Furthermore, personalized patient-specific information from these imaging modalities aids in guiding treatment decisions and monitoring postoperative interventions effectively. By characterizing flow patterns, these advanced imaging techniques hold great promise in improving the assessment and management of tetralogy of Fallot, providing tailored insights. However, further research and longitudinal studies are required to fully establish their clinical utility and potential impact on patient care.

RÉSUMÉ

La tétralogie de Fallot (TF) est la malformation cardiaque congénitale cyanogène la plus fréquente et elle requiert une correction chirurgicale. Bien que les interventions chirurgicales aient permis de diminuer considérablement la mortalité liée à la TF, des complications après ces interventions, comme la régurgitation de la valve pulmonaire (RP) ou la sténose, peuvent entraîner des issues cliniques défavorables, y compris la dysfonction ventriculaire droite et l'augmentation des risques de morbidité et de mortalité. Dans le présent article de synthèse, nous explorons le potentiel des techniques d'imagerie de pointe, y compris l'IRM de flux 4D et l'échocardiographie ultrarapide, pour obtenir des renseignements utiles sur la dynamique du débit sanguin et les paramètres énergétiques. Des mesures quantitatives, comme la perte d'énergie et la vorticité, pourraient permettre de mieux comprendre les paramètres hémodynamiques défavorables à un stade plus précoce où ils pourraient être plus facilement réversibles. De plus, des renseignements personnalisés obtenus par ces modalités d'imagerie peuvent contribuer à orienter les décisions thérapeutiques et à surveiller les interventions postopératoires pour chaque patient. La caractérisation des profils de débit sanguin par ces techniques d'imagerie s'annonce prometteuse pour améliorer l'évaluation et la prise en charge de la TF grâce à des renseignements personnalisés. Toutefois, des recherches supplémentaires et des études longitudinales devront être menées pour statuer sur leur utilité clinique et leurs répercussions possibles sur les soins offerts aux patients.

Tetralogy of Fallot (TOF) occurs in approximately 1 of every 2518 births, resulting in approximately 1660 cases per year in the United States alone.[1] Surgical repair is essential for these individuals to achieve a relatively normal and longer lifespan. Since 1955, the surgery has played a crucial role in reducing mortality by approximately 50%.[2–4]

However, right ventricular outflow tract (RVOT) dysfunction is highly prevalent, including pulmonary valve regurgitation (PR) and stenosis after initial repair.[5–7] This, in addition to frequent intraventricular rhythm disturbances,[8,9] leads to various serious consequences including right ventricular (RV) dilation, impaired RV function, reduced exercise capacity, arrhythmias, and elevated risks of morbidity and mortality.[10–12] As time passes after the surgery, there is an increased likelihood of requiring reintervention. The timing of these interventions requires clinical monitoring as well as by various imaging modalities, mainly ultrasound and magnetic resonance imaging (MRI).[13–15]

The prognostic significance of RV function in patients with repaired TOF (rTOF) is well established.[16–18] However, the early identification of imaging biomarkers predicting future RV dysfunction and irreversible remodelling remains a challenge.[19–22] This poses a challenge in clinical management centred around optimal timing of pulmonary valve

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replacement (PVR) to prevent long-term RV dysfunction and improve outcomes.[23,24] Although cardiac MRI plays a pivotal role in guiding therapy, the haemodynamic impact of PVR remains incompletely understood due to the limitations of conventional metrics in assessing RV size and function, which do not account for the intricate fluid mechanics and remodelling relationships within the heart.

It is believed that disturbances in cardiac fluid dynamics and energetics occur before observable morphologic changes take place.[25,26] Although flow patterns within the left ventricle have been extensively studied using cardiac MRI, particle imaging velocimetry echocardiography, and vector flow mapping (VFM), the characterization of RV flow dynamics in humans remains limited.

Recent advancements in imaging techniques have enabled the quantification of flow parameters such as vorticity, helicity, and energy loss (EL) using 4-dimensional (4D)-flow MRI. Moreover, the introduction of VFM has facilitated the assessment of EL as a predictive parameter for RV function after TOF repair.[27] High frame rate ultrasound (HFRUS) using plane wave imaging (Fig. 1)[28,29] and blood speckle tracking (BST) has further enhanced the ability to quantify blood speckle velocities, enabling direct quantification and visualization of blood flow vorticity and EL.[29,30] Velocity measurements, acquired through BST using high-frame-rate echocardiography, are devoid of any constraining assumptions and flow regularization. This approach, in contrast to methods such as VFM, does not require the assessment of wall velocities to calculate any aspect of blood velocity. However, this comes with the challenge of handling areas with signal dropout, akin to what is encountered in colour Doppler imaging.

The aim of this review is to provide an overview of novel imaging technologies, including cardiac MRI and ultrasound, and the valuable quantitative and qualitative flow parameters they offer in the study of TOF. These advanced imaging modalities provide valuable insights into the pathophysiology of the disease and could become part of the clinical decision-making.

Why Blood Flow Dynamics Might Be Important?

The influence of flow patterns on cardiac morphology and function is a multifaceted phenomenon.[31,32] It is believed that increased fluid shear stress impacts signalling pathways within the endocardium, influencing cardiac remodelling and function.[33,34] Disruptions in flow dynamics have been proposed to precede observable morphologic and functional changes.[26,35]

Advancements in MRI and ultrasound technologies have paved the way for the emergence of energy-based and quantitative haemodynamic imaging biomarkers.[36,37] However, their clinical utility needs to be established through longitudinal studies and outcome data. These flow dynamics have the potential to identify RV dysfunction at an earlier, adaptive stage after TOF repair, which might otherwise go unnoticed when relying solely on current imaging biomarkers.[38] TOF repair will have necessary negative residual lesions that all ultimately alter the transfer of potential energy in the myocardium to the blood pool, resulting in altered intraventricular flow dynamics, which is thought to preceded adverse remodelling.[25] The complex interactions between residual lesions after TOF repair and altered intracardiac haemodynamics are summarized in Figure 2 as well as where novel 4D-flow and HFRUS parameters can add insights.

Complementary Modalities

Cardiac ultrasound (echocardiography) and cardiac MRI are 2 important diagnostic tools for assessing cardiac structure and function, each having its own strengths and weaknesses and being fundamentally different in the physics involved and image reconstructions. Echo will generally have higher temporal resolution and be considered "real-time" imaging. It is generally more portable, available, and cost-effective than MRI. However, image quality depends on acoustic windows and is very operator dependent. It also has a limited role in tissue characterization. MRI, in comparison, has generally higher spatial resolution, does not depend on acoustic windows, and allows for far more advances volumetric and flow quantification, multiplanar imaging, and tissue characterization. The limitations include the expense and limited access, as well as the lack of "real-time" imaging reconstructed over multiple beats assuming steady haemodynamics throughout. Finally, some patients have counterindications to undergo MRI. Advancements in both modalities have improved on the strengths of each, whereas differences between both remain so that both modalities are to be regarded as complementary. HFRUS will be more suited to image the very short-lived intracardiac flow events or myocardial shear wave imaging, whereas 4D-flow MRI will be more suited to extracardiac flow patterns as well as 3D-flow visualization, with likely increasing overlap of both modalities in the future.

Qualitative and quantitative flow analysis

In rTOF, both EL and vorticity play significant roles in understanding the haemodynamics and functional outcomes.[37–39] EL refers to the dissipation of mechanical energy within the cardiovascular system, particularly in the RV, resulting from abnormal flow patterns and pathology. Vorticity, on the other hand, reflects the rotational component of fluid flow and plays a crucial role in evaluating flow dynamics within the heart. These vortices contribute to EL, affect ventricular function, and can potentially lead to adverse RV remodelling.[35] Factors such as pulmonary regurgitation, turbulent flow, adverse ventriculoventricular interactions contribute to abnormal flow dynamics in rTOF. These novel flow parameters can provide a new, more sensitive assessment of blood flow efficiency, ventricular function, and overall ventricular performance in addition to assessing progression longitudinally or after an intervention.

Furthermore, studies have identified ventricular kinetic energy (KE) as a promising noninvasive early indicator of ventricular efficiency. Pathologically turbulent flow has been associated with abnormal vascular remodelling, consistent with increased EL in rTOF patients with greater ventricular remodelling. Comparatively higher RV KE in patients with rTOF suggests increased workload on the RV to generate the same cardiac output as in healthy subjects. Future studies are needed to determine the predictive value of KE measurements for RV dysfunction and the optimal timing for reintervention.

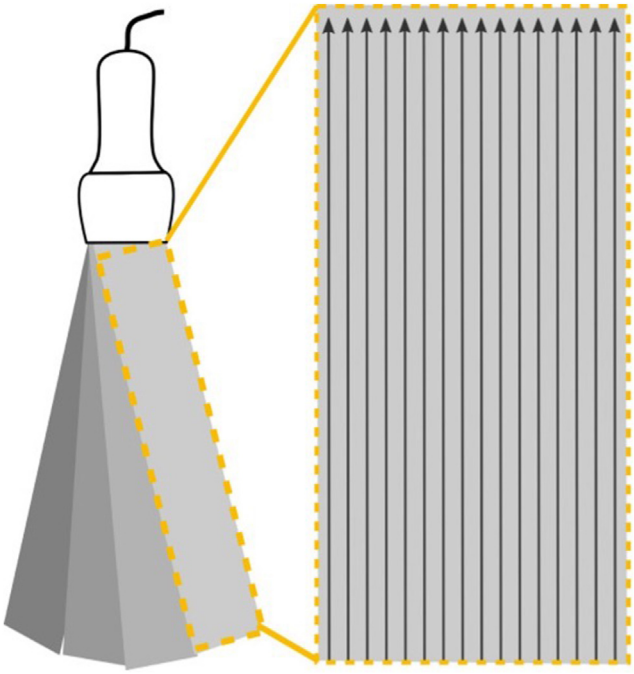

Figure 1. Plane wave imaging and parallel receive beamforming. A total of 3-9 plane wave directions to cover the Doppler sector width. For each plane wave transmitted, multiple image lines (16) were received simultaneously. Tracking can be done within the region covered by the 16 receive lines, where the frame rate equals the pulse repetition frequency. Adapted from Mawad et al.[38]

In addition to quantitative flow parameters, qualitative intracardiac blood flow analysis can play an important role in the evaluation of individuals with rTOF. By visually assessing the characteristics and patterns of blood flow within the heart, important insights can be gained about ventricular performance that would not have been recognized using conventional imaging. Abnormal flow patterns, such as stenosis, regurgitation, or swirling flow, can be identified through qualitative analysis.[38,40] Furthermore, qualitative analysis can help assess intervention effectiveness and monitor changes in flow patterns over time.

Assessing diastolic RV function and biventricular haemodynamics using 4D-flow cardiovascular magnetic resonance has the potential to serve as an important prognostic tool.[41] A restrictive RV filling pattern has been linked to slower recovery after repair.[42] By summing pulmonary valve flow and tricuspid valve flow, RV diastolic function can be evaluated in the presence of pulmonary regurgitation.[43] Altered flow haemodynamic forces have also been implicated in mechanical myocardial dyssynchrony in heart failure, cardiomyopathies, and TOF.[41]

Unique flow dynamics findings by ultrasound

Both *in vitro* and *in vivo* blood flow imaging in rTOF have described the same alterations in diastolic flow patterns. Mikhail et al.[44] demonstrate in an experimental heart simulator that PR has a significant effect on RV flow, primarily by impeding diastolic inflow through the tricuspid valve and increasing the dissipation of viscous energy within the RV. Similar findings were made *in vivo* by Mawad et al.,[38] using HFRUS and BST. In patients with atrial septal defect and rTOF, diastolic energy losses in the dilated RVs were found to be similar but significantly higher than healthy controls. This suggests that the dilated RV is less efficient, with more energy being lost during diastole. The study also identified a unique pattern of diastolic EL in patients with rTOF, specifically in the RV apex, which was not observed in the other groups (Fig. 3). This pattern was attributed to the collision of jets from pulmonary regurgitation and tricuspid inflow at the RV apex. The clinical significance of these findings is not yet clear, but studying disturbances in RV flow and EL patterns may provide insights into the origin of apical dysfunction in the dilated RV of patients with rTOF.

Although the study did not establish a direct link between RV flow dynamics and RV function or mechanics, it found that quantifying blood flow energy losses and vorticity using BST is indeed feasible, and this method showed low variability between observers. However, the research brought to light essential considerations concerning image acquisition and postprocessing, factors that can affect the accuracy of blood speckle velocity and EL measurements. Similar to other Doppler-based methods for blood flow measurements, multiple acquisitions are analysed to optimize alignment with the blood flow direction. In the same vein, BST velocities derived from high-frame-rate echocardiography can benefit from real-time visualization and analysis. Another limitation worth noting is the 2D nature of this imaging technique, which does not account for through-plane variations (Fig. 4), particularly due to the crescent shape of the RV. The RV 4C view's imaging plane is nearly perpendicular to the direction of systolic flow towards the outflow tract, causing the loss of the through-plane component of systolic RV flow. Calculations of EL depend on smoothing parameters in HFRUS, and maintaining their consistency helps avoid errors related to this aspect. Being aware of these limitations is crucial for future studies, but these limitations can potentially be mitigated with the availability of real-time visualization and analysis tools.

Shear-Wave Imaging by Ultrasound

Harnessing the exceptionally high temporal resolution possible with HFRUS (approximately 1000 frame per second), mechanical wave velocities can be measured as they propagate through the myocardium following a natural event such as valve closure or a generated mechanical wave.[45,46] Their velocity is proportional to myocardial stiffness, which can be affected by abnormal perfusion, abnormal loading conditions, or histologic changes such as myocardial fibrosis. Salles et al.[47] have developed a 3D HFRUS sequence able to provide mechanical wave propagation maps *in vivo*. The value of these applications in rTOF remains to be investigated but can be an additional tool to understand patient-specific physiologies and a tissue characterization tool using ultrasound.

4D-Flow MRI Parameters

Historically, measuring the blood flow has been considered a far greater challenge than measuring the blood pressure with majority of clinical decisions being driven by blood pressure

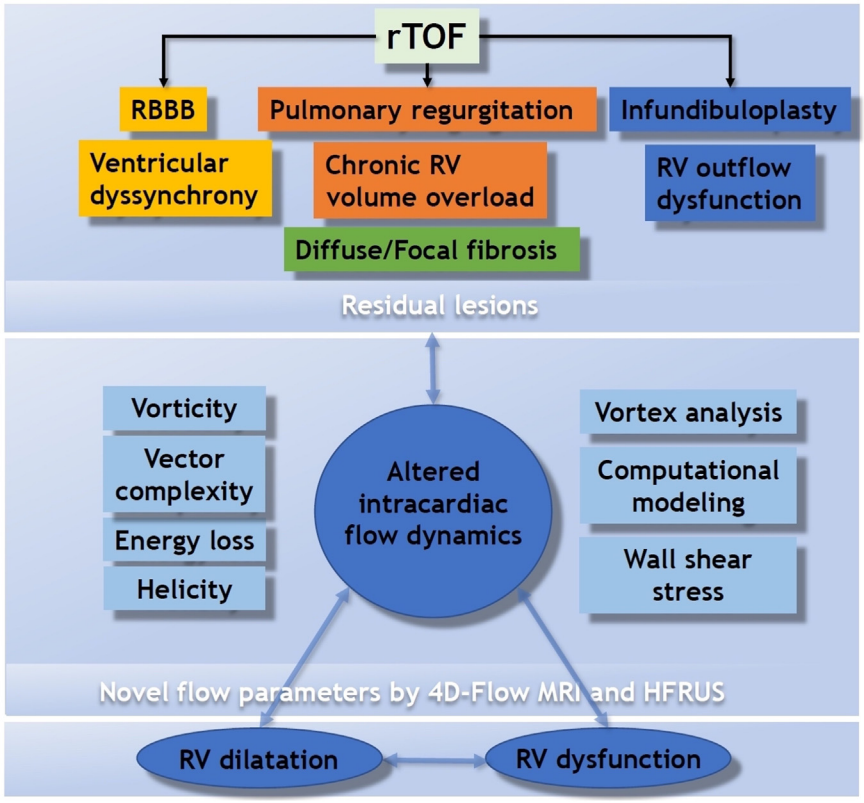

Figure 2. Residual lesions in repaired tetralogy of Fallot (rTOF) resulting in altered intracardiac ventricular flow dynamics and adverse right ventricular (RV) remodelling and dysfunction. High frame rate ultrasound (HFRUS) and 4D-flow magnetic resonance imaging (MRI) can quantify these flow alterations with novel quantitative flow parameters. RBBB, right bundle brach block.

measurements, yet our tissues survive on adequate perfusion not a pressurization. 4D-flow MRI has emerged as a promising technology that provides concise and rapid *in vivo* 3D visualization of complex and aberrant blood flow formations inherent to congenital cardiac anomalies and the surgical techniques necessitated for successful palliation. The comprehensive acquisition of velocity fields in all Cartesian directions over any anatomic region of interest has enabled the measurement of novel qualitative and quantitative haemodynamic parameters of previously unattainable diagnostic, therapeutic, and prognostic significance. Recent studies applying 4D-flow MRI with cardiovascular imaging have demonstrated the ability to measure blood flow forces acting on the vessel wall (wall shear stress—WSS), energy dissipation due to aberrant or turbulent flow, and viscous EL mediated by secondary flow formations characterized by helical or vortical flow. Increasing technologic capability has inspired collaborative research advancements and stimulated multidisciplinary clinical adoption. With the emergence of multicentre trials, applying 4D-flow MRI within cardiovascular diagnostics, promising prognostic implications including the identification of optimal flow-tissue relationships, risk stratification capabilities for deleterious ventricular and vascular remodelling, quantitative flow calculations, and evaluation of complex interdependent haemodynamic relationships have been defined.

Surgical reconstruction of congenital heart disease must correct potentially fatal cardiovascular lesions such that perfusion in the systemic and pulmonary circulation is life sustaining, all while minimizing circulatory resistance and the potential for future complication. The complexity and heterogeneity of TOF and other conotruncal lesions dictates patient-specific surgical solutions that inherently limit our ability to perform controlled studies to define prognosis and optimal treatment strategies both before and after surgical correction. Inherent to both catheter-based and surgical interventions for congenital heart disease is the demand for unique, patient-specific treatment plans that are founded on well-established technical principles that are applied in individualized, improvisational, and artistic ways. 4D-flow MRI is a patient-specific and noninvasive approach with promising potential for application in pre- and postoperative assessment that can describe even the most complex flow patterns in heterogeneous congenital lesions including conotruncal anomalies (Fig. 5). With the capability to extract spatial and temporally resolved blood flow specific biomarkers, 4D-flow MRI has the potential to revolutionize our understanding of complex and dynamic cardiovascular relationships that have been previously undefined within congenital heart disease, supporting a role for this imaging strategy in therapeutic planning, postinterventional assessment, and longitudinal evaluation of surgical outcomes.

Pulmonary regurgitation remains a common clinical sequela after rTOF. The timing and method of PVR present some of the most controversial questions in congenital heart disease. However, the increasing preponderance for right-

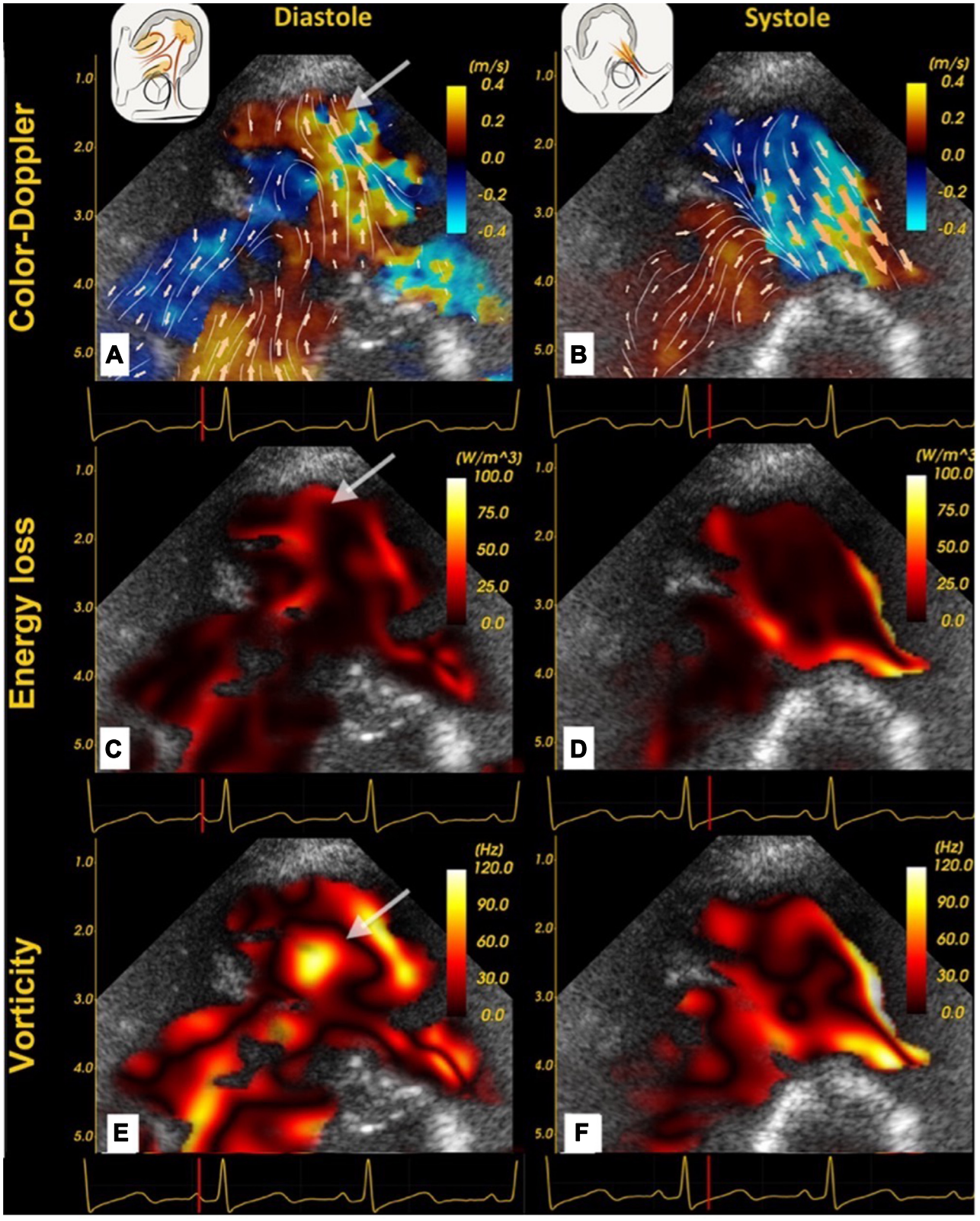

Figure 3. Typical examples of right ventricle intracardiac velocities, energy loss, and vorticity mapping in diastole and systole in repaired tetralogy of Fallot. In diastole, regurgitant pulmonary flow collides with the tricuspid inflow, resulting in disorganized apical vortices (**A**, indicated by a **white arrow**) with an additional area apical energy loss and vorticity (**C, D**, indicated by a **white arrow**). The schematic in the upper left of each panel illustrates the imaging plane and areas of high energy loss in orange. Adapted from Mawad et al.[38]

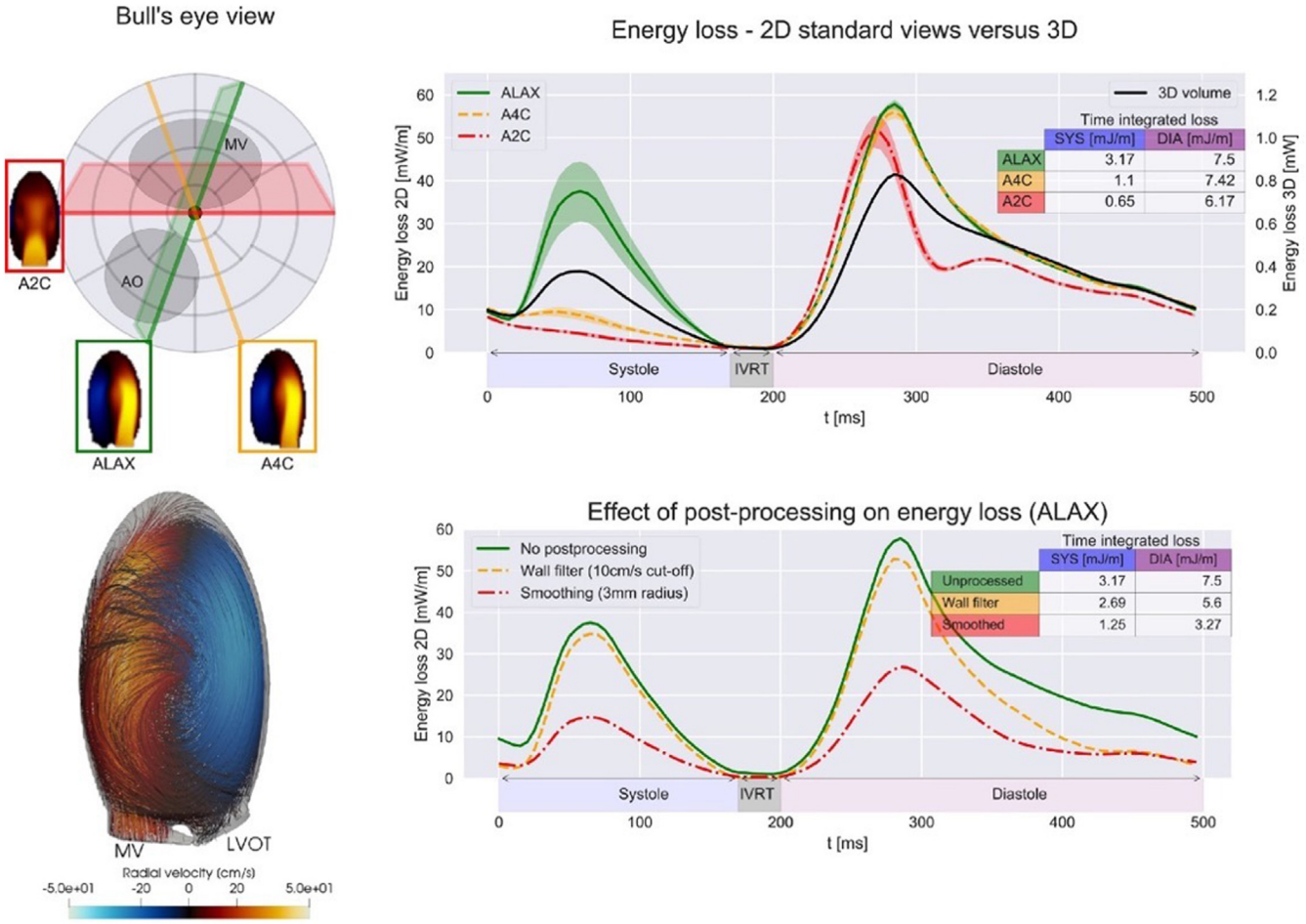

Figure 4. Analysis of the energy loss metric in a computer simulation model mimicking 3D ventricular flow. Bottom left: snapshot of the flow pattern in the model in late diastole. Upper left: bull's eye view marking the mitral valve and outflow tract of the phantom along with the imaging plane/position of the selected standard examination views. Top right: the energy losses for standard views are traced along with variation resulting from the ±5° change in angle in the shaded lines. Little variation is noted in diastole, with some more important variations in systole from the ALAX view. Bottom right: the influence of the estimated values after postprocessing operations is plotted for the ALAX view with varying degrees of smoothing parameters. This indicates that increasing spatial smoothing reduces the EL magnitude but retains the curve shape (**red dotted line**). Wall filtering (**yellow line**) has a little effect on EL magnitude and curve shape. ALAX, apical long axis; AO, aorta; A2C, apical 2-chamber; A4C, apical 4-chamber; DIA, diastolic; EL, energy loss; IVRT, isovolumic relaxation time; LVOT, left ventricle outflow tract; MV, mitral valve; SYS, systole. Adapted from Mawad et al.[38]

sided imaging studies that include 4D-flow data also illustrates the consequences of such defects not only for the RV function and pulmonary arterial (PA) vasculature but also for the left ventricular (LV) function and ascending aorta. Numerous studies report a high incidence of aortic dilation and aortic valve disease along with abnormal flow haemodynamics in patients with rTOF.[48–51] Despite clear abnormalities in flow patterns, and shear and wall stress in the aorta, the incidence of aortic dissection or rupture in patients with repaired conotruncal defects and TOF per se remains vanishingly rare.[48,50] Although aortic root–related complications are rare in children and young adults, the risk for development of significant aortic aneurysms and aortic valve disease is considerably higher in older patients with rTOF.[48,52] Furthermore, long-term RV volume overload has been associated with impaired biventricular filling, typically associated with diastolic dysfunction.[53–56] 4D-flow MRI has been shown to be useful in describing the pathologic flow in all aforementioned instances and has been related to conventional markers of disease severity, with sensitivity to detect the flow haemodynamic changes after PVR.

Pulmonary flow in TOF

Abnormalities of the RVOT are a cardinal feature of TOF, predisposing the proximal pulmonary arteries to highly aberrant flow formations mostly due to altered flow trajectory and anatomy after surgical or interventional repair.[57] Irregular and retrograde pulmonary flow increases the RV afterload and has been shown to be associated with the remodelling of proximal pulmonary arteries.[56,58,59] Comprehensive 4D-flow MRI evaluation of patients with rTOF has been shown to be more accurate than standard 2D velocity encoding phase-contrast MRI due to complexity of 3D flow in pulmonary arteries.[39,43] Early 4D-flow MRI studies concerning TOF qualitatively described large-scale helical and vortical flow

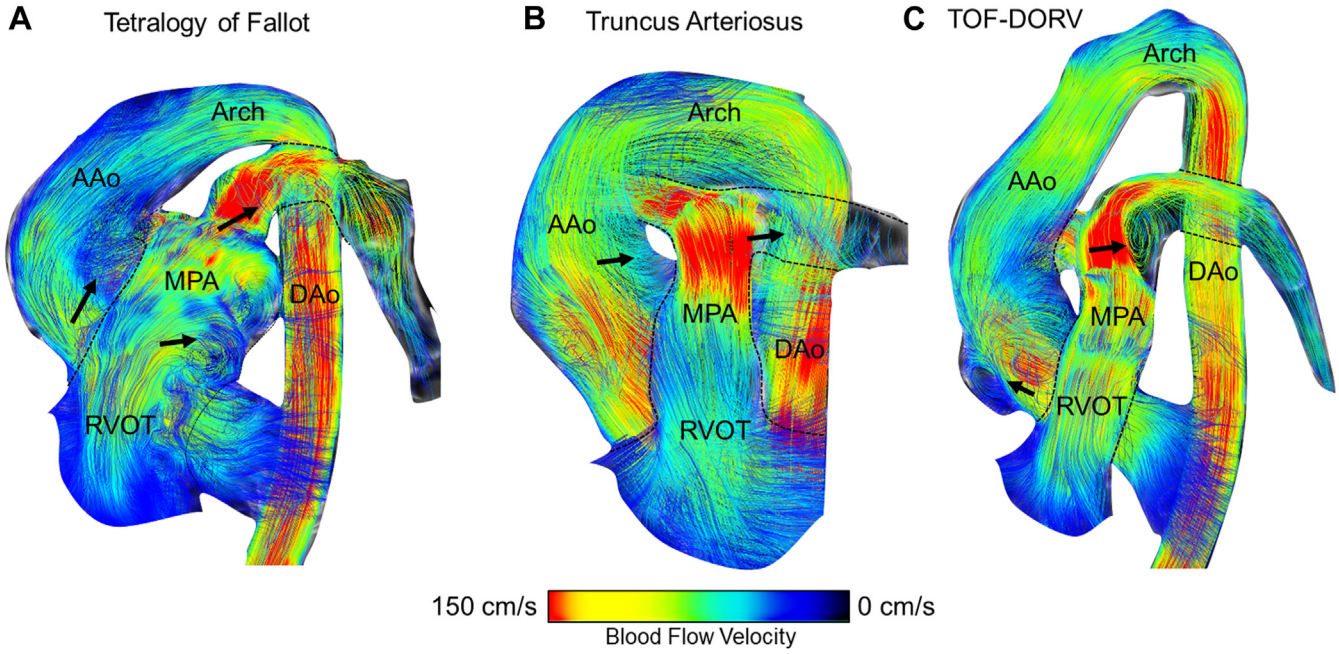

Figure 5. Comprehensive flow haemodynamic evaluation of patients after the surgical repair of different conotruncal lesions. (**A**) An example of typical 4D-flow haemodynamic patterns in a teenage patient with tetralogy of Fallot (TOF) who underwent initial repair using transannular patch, showing distorted flow through pulmonary arteries in the form of recirculating vortices (**arrows**). One can also appreciate the prominent helix along the inner aortic curve. (**B**) Supraphysiologic helical flow along the inner curve of the aorta is also visible in a patient with truncus arteriosus. In addition, there is a strong helical flow in the left pulmonary artery. (**C**) Patient with TOF-type double outlet right ventricle (DORV) revealing small aneurysmal dilation inside the aortic root. Furthermore, there is a large vortex recirculation in the posterior aspect of the main pulmonary artery. AAo, ascending aorta'; DAo, descending aorta; MPA, main pulmonary artery; RVOT, right ventricular outflow tract.

formations present in proximal pulmonary arteries[60] (Fig. 6). Recently, Robinson et al.[59] applied a quantitative approach to describe flow through the RVOT and pulmonary arteries in children after TOF repair using 4D-flow MRI-derived KE. The authors reported a size- and stroke volume—adjusted increase in systolic- and diastolic flow—mediated KE, which was further associated with RV size and the degree of pulmonary regurgitation. Fredriksson et al.[61] reported elevated 4D-flow MRI-derived turbulent KE in the RVOT and PA. Although the calculation of turbulent KE requires more complex 4D-flow MRI sequences and postprocessing, it offers a very specific and valuable approach for detection of turbulent flow and its associated EL. The authors further showed that elevated turbulent KE was more strongly associated with pulmonary regurgitation and RV dilation compared with conventional 2D phase-contrast MRI indices. McLennan et al.[57] recently reported that flow-mediated viscous EL measured in the proximal pulmonary arteries is associated with the RV power in patients with rTOF. Future studies may focus on characterization of flow haemodynamic variances with respect to the subtype of TOF and surgical approach (ie, transannular patch vs RV-PA conduit). In summary, a combination of reduced PA distensibility and abnormal outflow tract geometries giving a rise to aberrant flow structures would indicate that 4D-flow MRI might be a beneficial tool for the longitudinal follow-up of patients with TOF to monitor proximal PA remodelling after the primary repair and before and after the subsequent PVR.

Aortic flow in conotruncal lesions

Aortopathy is an increasingly more appreciated comorbidity of conotruncal lesions. Although the aortic root dilation is common among children and adolescents with TOF, it is rarely associated with the aortic valve complications at young age.[62] The aortic root dilation typically persists between 30% and 51% of patients and is typically associated with late surgical repair after 12 months of age.[48,50,63] Recent work by Egbe et al.[48] reported that 12% of patients develop later in adulthood significant aortic valve disease or aortic aneurysm with 29% of those patients requiring surgical intervention. Relatively recent efforts have described 4D-flow MRI aortic flow characteristics including supraphysiologic systolic helical flow in children with TOF who underwent early surgical repair before 12 months of age and had normalized ascending aortic diameter.[51] The authors further described increased WSS throughout the thoracic aorta and increased aortic stiffness, thus mimicking the flow haemodynamic conditions observed in patients with bicuspid aortic valve aortopathy.[64] Haemodynamic WSS has been associated with aortic dilation and stimulation of endothelial signalling pathways augmenting the vascular remodelling towards stiffer character.[65] Abnormal aortic flow patterns in TOF have also been described in terms of flow-mediated viscous EL,[66] helicity and vorticity,[67] and abnormal outflow tract geometry.[68] Although long-term outcomes and longitudinal evaluation of the effect of aortopathy on LV function in patients with TOF are not available, several studies have already related the degree of

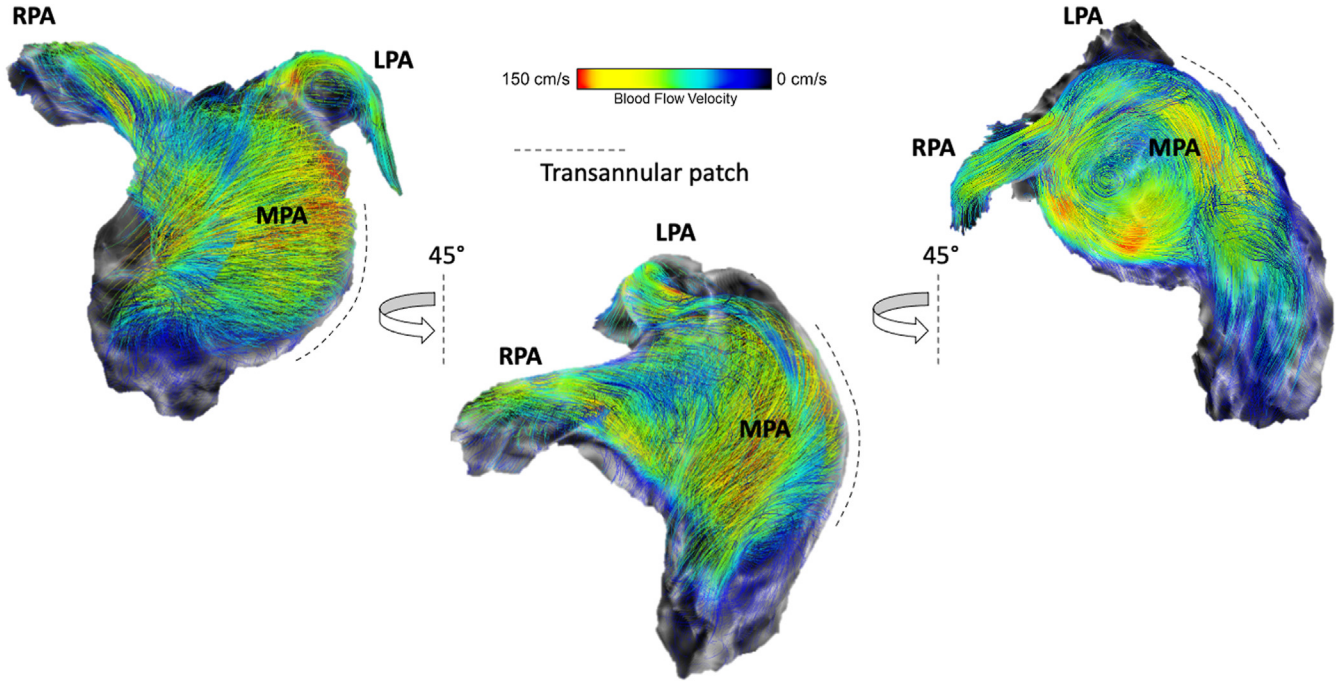

Figure 6. Pulmonary arterial flow visualization using the 4D-flow magnetic resonance imaging in an adult patient with repaired tetralogy of Fallot by transannular patch. One can appreciate the abnormal flow pattern at the dilated region bounded by transannular patch. Vortical recirculation at this region gives rise to abnormal inflow to branch pulmonary arteries, which can further remodel vascular shape and vessel wall character. LPA, 'left pulmonary artery; MPA, main pulmonary artery; RPA, right pulmonary artery.

aortic stiffness to the LV function known to be predictive of arrhythmia and sudden cardiac death in this patient population.[69,70]

Intracardiac flow in conotruncal lesions

Intracardiac flow visualization has recently gained interest as an early indicator of ventricular diastolic dysfunction, which has clinically important prognostic value in patients with congenital heart disease.[71–73] Chronic volume overload due to pulmonary insufficiency results in progressive ventricular dilation and diastolic dysfunction. Despite the large amount of work suggesting that subsequent PVR should be guided by ventricular dilation, more sensitive and comprehensive markers indicative of ideal time for PVR are needed.[5] Both RV and LV diastolic dysfunction have recently been advocated to be investigated by means of fluid-tissue interactions and large-scale vortex formations. The premise being that changes in the ventricular flow domain would be detectable sooner than early-stage tissue stiffening and remodelling.[74] In this setting, 4D-flow MRI has arguably the best 3D spatial-velocity capabilities from all currently available intracardiac flow visualization techniques.[73,75] Numerous flow haemodynamic markers have been designed for the investigation of the inflow patterns through atrioventricular valves including qualitative vortex grading, quantitative spatiotemporal vorticity calculations, intraventricular pressure gradients, particle tracking with respect to end-diastolic volume partition, and vortex energetics.[76–80] Because the intracardiac flow patterns and vortex formations are related to both ventricular remodelling and the status of mitral and tricuspid valves, comprehensive 4D-flow MRI mapping can provide valuable status immediately after surgical intervention and in long-term follow-up.[81]

Blood flow to both ventricles is primarily driven by pressure gradients and myocardial compliance. Biventricular restrictive physiology after surgical repair of TOF has been described using late gadolinium enhancement and by myocardial deformation analysis to determine the extent and effect of fibrosis formation.[82–84] However, previous studies have suggested that flow haemodynamic evaluation of the ventricular inflow patterns might proceed noticeable diastolic dysfunction as typically described by changes in tissue Doppler patterns.[71,80] One of the most frequently investigated flow haemodynamic markers is a vorticity—spatial derivative of velocity vector field that can be calculated instantaneously at any point of cardiac cycle. The theoretical background behind vorticity calculation and its physiological meaning has been described elsewhere.[85] The most accurate flow dynamic description defines vorticity as a local spinning motion of any fluid. From the clinically practical perspective, vorticity measures flow cohesiveness and how much velocity changes with respect to the flow direction (Fig. 7). Strong and cohesive ventricular inflow, as observed in the state of healthy compliant ventricle and optimal preload, will then produce a high vorticity field. Conversely, reduced pressure filling gradient and chaotic inflow are typically associated with restrictive ventricular physiology, producing reduced vorticity. Decreased ventricular vorticity in the context of diastolic dysfunction has been observed in patients with pulmonary hypertension, chronic obstructive disease, heart failure, and cardiomyopathies.[77,80,86]

Hirtler et al.[37] investigated the RV inflow of patients after repair of TOF using 4D-flow MRI-calculated vorticity.

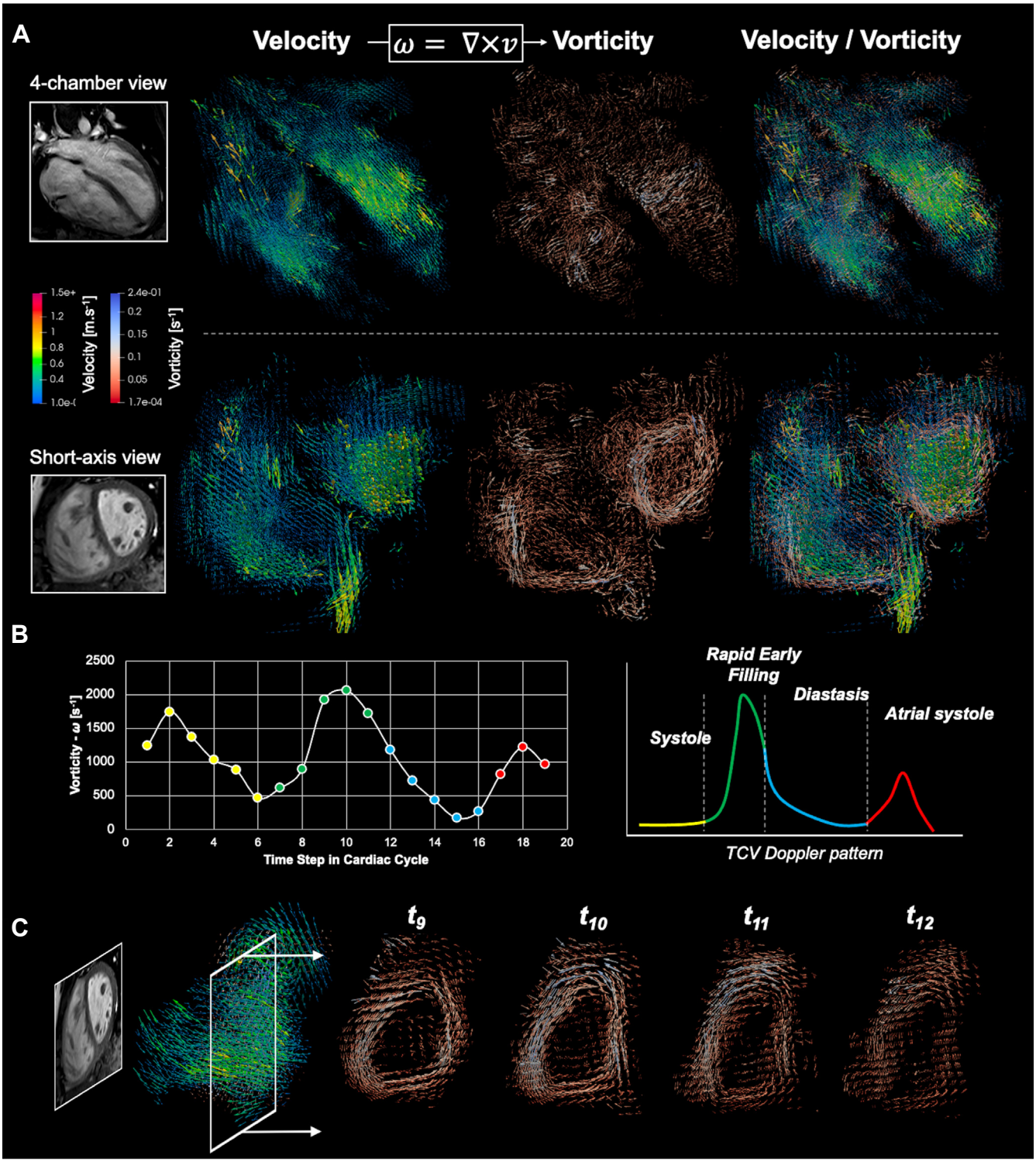

Figure 7. Analysis of the intracardiac flow and right ventricular (RV) diastolic function using 4D-flow magnetic resonance imaging—derived vorticity fields. (**A**) The very right-top panel shows the plot of velocity and vorticity vector fields during early diastole for both ventricles from the 4-chamber and short-axis view perspectives. (**B**) Middle panel portrays RV vorticity plotted throughout the cardiac cycle along with a typical Doppler waveform. (**C**) Isolated RV vorticity vector field from the short-axis view perspective sampled from early diastole. TCV, tricuspid valve.

Surprisingly, the authors reported a slight increase in vorticity measured inside the RV cavity of patients with TOF. However, this result is affected by the presence of pulmonary regurgitation, which produces an enhanced vorticity vector field within the RVOT. Consequently, the interpretation of the intracardiac flow indices must be always done with respect to the functional status of related valves. Additional encouraging findings in the aforementioned study were the observed negative relationships between sampled vorticity and RV size, suggesting that dilated less compliant ventricle does not generate sufficient negative pressure gradient for efficient filling. A more recent study by Elsayed et al.[87] showed a relationship between higher vorticity values calculated in the RV and biventricular shape changes including longer ventricular length and a tricuspid valve morphology and function. The interventricular interdependency in TOF late after repair has been further demonstrated by abnormal LV filling patterns using 4-flow component analysis in patients with normal ejection fraction.[88] Another recent study by Sjöberg et al.[53] found reduced early diastolic RV KE in patients with TOF with restrictive RV disease. The authors further described variable changes in KE as a response to different surgical techniques for PVR, with the widening of the outflow tract resulting in an increase of KE. The same group later described abnormal distribution of flow haemodynamic forces calculated from the 4D-flow MRI-derived pressure gradients with normalization after the PVR.[41]

Computational Modelling in rTOF

Ventricular remodelling in rTOF can also be studied through advanced ventricular geometric assessment using computational modelling. Using statistical shape modelling and patient-specific geometric models derived from cardiovascular magnetic resonance images, some patient-specific features and prognostic factors can be brought to light. Shape-function correlations have shown that specific variations in ventricular shape were linked to changes in systolic wall motion. Notably, differences in RV apical dilation and LV dilation were associated with changes in systolic wall motion that partially explained variations in systolic function. Myocardial properties can also be elucidated using computational modelling. RV apical dilation seemed to indicate increased RV basal and apical contractility, potentially serving as a compensatory mechanism to preserve LV function and prevent dilation. Conversely, variations in RV basal bulging and LV conicity had an opposing impact on systolic function. Although these shape changes might also relate to contractility in specific regions, their overall influence on global function was primarily due to the shape itself. These shape-function relationships are relevant for managing patients with rTOF, aiding in outcome prediction and clinical decision-making. There are limitations to these techniques, namely simplifications in modelling algorithms and omission of interactions with other structures, such as the lungs and the chest wall.

Conclusions

Although TOF repair has greatly reduced mortality, post-repair complications such as PR and stenosis remain common and can lead to adverse outcomes, including impaired RV function and increased risks of morbidity and mortality.

Advanced imaging techniques such as 4D-flow MRI and high-frame-rate echocardiography provide valuable insights into blood flow dynamics and ventricular energetics. Quantitative flow parameters such as EL and vorticity, along with qualitative flow analysis, can play important roles in evaluating haemodynamics and detecting adverse ventricular flow dynamics at earlier, more reversible stages as compared with conventional markers. They also provide patient-specific information, helping to guide treatment decisions and monitor postoperative interventions effectively.

Overall, these advanced imaging technologies hold promise in the assessment and management of rTOF, offering personalized insights and hopefully improved patient outcomes. However, further research and longitudinal studies are needed to establish their clinical utility fully.

Ethics Statement

All research reported has adhered to the relevant ethical guidelines.

Patient Consent

The authors confirm that patient consent is not applicable to this article as this is a review article using published material.

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Disclosures

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