The right ventricle in congenital heart disease

P A Davlouros, K Niwa, G Webb, M A Gatzoulis

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In patients with congenital heart disease the right ventricle (RV) may support the pulmonary (subpulmonary RV) or the systemic circulation (systemic RV). During the last 50 years evidence is accumulating that RV dysfunction develops in many of these patients and leads to considerable morbidity and mortality. Therefore RV function in certain groups of congenital heart disease patients needs close surveillance and timely and appropriate intervention to optimise outcomes. Despite major progress being made, assessing the RV either in the subpulmonary or the systemic circulation remains challenging, often requiring a multi-imaging approach and expertise (echocardiography, magnetic resonance imaging, nuclear and occasionally invasive assessment with angiography). This review discusses the implications of volume and pressure loading of the RV in the context of congenital heart disease and describes the most relevant imaging modalities for monitoring RV function.

The exploration and understanding of the heart's morphology, physiology, and function both in health and disease remains a challenging and still evolving field. Modern imaging modalities, mainly echocardiography, but also radionuclide imaging and lately computed tomography (CT) and cardiac magnetic resonance (CMR), have revolutionised clinical research on biventricular anatomy and function.^{1–6} However, there are still numerous questions to be answered regarding left and right ventricular function and their contributions to cardiovascular disease prognosis.

Although LV function and dysfunction and its relationship to prognosis have been studied extensively, the role of RV morphology, function, and dysfunction in cardiovascular disease has not attracted the interest of scientists until recently. This was largely due to the fact that most acquired cardiovascular diseases affect primarily the left ventricle. Additionally, the RV has a very complex shape, which makes precise in vivo imaging and assessment challenging for most imaging modalities.

RV morphology and function is, however, of paramount importance in the rapidly growing field of congenital heart disease (CHD). Many CHD patients have become adolescents and adults thanks to major advances of paediatric cardiology and cardiac surgery in the latter half of the last century. This has created a patient population (adult CHD patients) in which the RV is often the centre of attention.^{7–11} Such patients are unique models for the study of RV physiology and function. Accurate assessment of RV anatomy, volume, and ejection fraction in CHD, both before and after reparative surgery, requires one or more of the following imaging modalities: echocardiography, contrast angiography, radionuclide studies, CT, and or CMR.¹²

RIGHT VENTRICULAR MORPHOLOGY AND IMAGING

Echocardiography is the imaging modality of choice for the assessment of left ventricular function. However, most

quantitative two dimensional echocardiographic measurements of ventricular performance are based on geometric assumptions that do not apply to the RV. The left ventricle is more conical in shape and has a wall thickness 3–4 times greater than the RV free wall.¹³ RV trabeculations are coarse compared to the finely trabeculated left ventricle and the RV outflow tract is muscular and elongated, ending up in the pulmonary valve which does not have a real valvar annulus.¹⁴ These differences in ventricular morphology reflect the genetically determined different role the two ventricles are called to play in the circulation.¹⁵ Sir Magdi Yacoub described the left ventricle as a “flask” shape with the inlet and outlet sharing one orifice, enabling it to deliver a bolus of blood against high resistance, and the RV as a flattened tube wrapped around the left ventricle with separate inlet and outlet orifices and a presumed contraction pattern simulating peristalsis, an arrangement suited for pumping blood against low resistance.¹⁶

Having these important differences in mind we will briefly refer to imaging methods for the evaluation of RV anatomy and function and then examine the RV and the applicability of these methods in two broad contexts: the volume loaded RV, and the pressure loaded RV.

Angiographic assessment of the RV is invasive, involves ionising radiation and use of contrast agents, and is not as accurate as CMR¹² (fig 1). It used to be the gold standard for RV evaluation in the early era of imaging, but has largely been replaced by newer “non-geometric” techniques like three dimensional (3D) echocardiography, CMR, and multislice CT (MSCT), which permit accurate assessment of RV volume, mass and function.^{2–4 17–20}

Indirect insights into RV systolic and diastolic function are given by conventional Doppler indices such as the duration of systolic time intervals derived by interrogation of the RV outflow¹ and Doppler recordings of the tricuspid inflow and hepatic venous flow.^{1 21} M mode and tissue Doppler imaging examine myocardial velocities and time intervals, detectable at the level of the tricuspid annulus, as markers of RV systolic and diastolic longitudinal motion¹ (fig 2). Diastolic tricuspid annular velocities, in contrast to inflow velocities, correlate with invasively determined RV pressures.^{22 23} Nongeometric and load independent, Doppler derived quantitative indices of global ventricular function, like the myocardial performance index (Tei index),^{24 25} or tricuspid annular isovolumic acceleration,^{26–28} may prove useful for evaluation of RV function. However, they correlate weakly with echocardiographic RV ejection fraction²⁹ and they have not been validated against quantitative methods of evaluation of RV function like CMR.^{22 25 30} Transoesophageal echocardiography (TOE) has better sensitivity and specificity for evaluation of CHD compared to transthoracic echocardiography, but it is

Abbreviations: ASD, atrial septal defect; ccTGA, congenitally corrected transposition of the great arteries; CHD, congenital heart disease; CMR, cardiac magnetic resonance; CT, computed tomography; MRI, magnetic resonance imaging; MSCT, multislice computed tomography; PR, pulmonary valve regurgitation; RNA, radionuclide angiography; RV, right ventricle; TOE, transoesophageal echocardiography; TR, tricuspid regurgitation

Figure 1 Right ventricular angiography, right anterior oblique (RAO) projection, end systole. Severe pulmonary valve stenosis. There is thickening and doming of the pulmonary valve (white arrow), secondary narrowing of the right ventricular outflow tract due to muscle hypertrophy, and poststenotic dilatation of the pulmonary artery. PA, pulmonary artery; RV, right ventricle; RVOT, right ventricular outflow tract.

semi-invasive, not well suited for evaluation of an anteriorly positioned RV, and requires special skills.³¹

Radionuclide angiography provides a reliable quantitative measurement of ventricular function that is not based upon assumptions of ventricular geometry, and its value in the routine clinical measurement of ventricular function is well established.^{12–32} However, it requires the acquisition of views of the ventricles that exclude counts from other chambers, which can usually be achieved for the left ventricle, but often not satisfactorily for the RV.³³ Radionuclide imaging uses ionising radiation, although the radiation dose is low compared to cineangiography.³³ Additionally this modality requires an adequate bolus injection for first pass studies, and a regular rhythm with minimal R-R variability.¹² Its resolution is poor compared to more modern imaging methods. Finally, investigation of CHD has focused more on structural rather than functional abnormalities, although this is changing. Radionuclide imaging has, thus, been of limited use to date.³³

Rapid advancements in the field of CMR have established this technique as the gold standard for quantitative assessment of RV volume, mass, and function regardless of its position in the thorax (subpulmonary v systemic RV).^{4–18–20–34} Spin echo (black blood) sequences are used for exploration of

Figure 2 M mode echocardiogram of the lateral (free wall) tricuspid valve annulus. The height of the annular movement (white double arrow) is a surrogate marker of RV systolic function.

anatomy and gradient echo (white blood) sequences for assessment of RV function.³⁵ Flow velocity mapping allows for accurate assessment of valvar regurgitation (regurgitant fraction) and magnetic angiography for assessment of great vessel anatomy.³⁶ CMR with late gadolinium enhancement can detect myocardial fibrosis in both ischaemic and non-ischaemic cardiomyopathies.^{37–38} This technique has now been applied to CHD and is likely to make an important contribution to our understanding of the pathophysiology of RV dysfunction.³⁹ However, CMR has also limitations. It usually requires breath-holding, a regular heart rhythm, exclusion of patients with implantable metallic devices, and it has high cost with low availability at present.³⁹ MSCT is emerging as an alternative modality, especially for patients with implantable devices (contraindication for CMR); however, MSCT uses ionising radiation and requires a low heart rate for image acquisition.^{2–3}

THE VOLUME LOADED RV

Three of the most common lesions associated with RV volume loading will be examined: atrial septal defect, significant pulmonary valve regurgitation, and significant tricuspid regurgitation.

Atrial septal defect (ASD)

There are three major types of ASDs: ostium secundum, ostium primum, and superior sinus venosus defect.⁴⁰ An isolated ASD results in left-to-right shunting, which when significant, leads to right atrial/ventricular and pulmonary arterial dilatation. These features are often evident on chest x ray (postero-anterior and lateral). Transthoracic echocardiography is invaluable for diagnosing an ASD and assessing its impact on RV size and function^{40–41} (figs 3–5). TOE may be needed to diagnose a sinus venosus defect and assist in assessment of pulmonary venous drainage.^{40–42} Paradoxical septal motion as a result of RV volume loading is evident both in M mode and 2D echocardiograms in most patients^{41–43–44} (fig 6).

The RV tolerates volume loading well for a long time.⁴⁰ Although delayed RV contraction has been detected with radionuclide studies (in the absence of conduction defects),⁴⁵ echocardiographic assessment has shown RV systolic and diastolic function to be normal or exaggerated.^{46–47} In older

Figure 3 Two dimensional echocardiogram, apical four chamber view. There is dilatation and hypertrophy of the right ventricle, which is larger than the left ventricle. The right ventricular inflow diameter (dotted line), measures 5.27 cm (normal adult diameter < 4 cm). A large atrial septal defect (ASD) is present (white arrow). LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

Figure 4 Two dimensional echocardiogram. Left panel: Subcostal four chamber view. There is a large (23 mm) ostium secundum ASD (dotted line). Right panel: Same patient in the left panel. Subcostal short axis view at the level of the great vessels. The relation of the ASD with the aortic root can be assessed. Ao, aortic root; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle; RVOT, RV outflow tract.

patients with long standing volume overload, regional RV tissue Doppler imaging may disclose early relaxation abnormalities even with normal traditional tricuspid inflow velocities.⁴⁷

It is now accepted that long standing right heart, pulmonary arterial and venous volume overload and dilatation in the setting of an ASD is detrimental and leads to morbidity (heart failure, arrhythmia, and thromboembolic events) and increased mortality.⁴²⁻⁴⁸ These can all be reversed to variable degrees with catheter or surgical closure of the defect.⁴⁸⁻⁴⁹ However, atrial arrhythmias may persist or develop in adults repaired after the age of 40 years.⁴⁸⁻⁵⁰⁻⁵³ Indeed, RV/RA remodelling is incomplete in the older patient undergoing transcatheter closure.⁵⁴ Therefore early defect closure is warranted if a significant shunt (with right heart dilatation) is present.¹⁰⁻⁴⁰⁻⁴⁸

Transcatheter ASD device occlusion has become the treatment of choice for most secundum ASDs. While many devices are being used for this purpose, the Amplatzer ASD occluder (AGA Corporation, Golden Valley, Minnesota, USA) is most widely used at present⁵⁵⁻⁵⁶ (fig 7, 8). With appropriate patient selection, device closure in adults leads to sympto-

matic improvement and increased exercise capacity even in asymptomatic patients and is associated with fewer complications and shorter hospitalisation times compared to surgery.⁵⁷⁻⁵⁸ However, very long term results are lacking at present.

Dilatation of the RV may not subside after ASD closure,⁵⁹ in some patients up to five years after repair.⁶⁰ Others have reported progressive normalisation of RV size during 1–24 months after surgical or device closure.⁵⁴⁻⁶¹⁻⁶² Atrial “shrinkage” is inversely proportional to age at repair and is related to the potential for atrial arrhythmias after late defect closure.⁵³⁻⁶¹ In patients with normal diastolic function, increased RV myocardial diastolic and systolic velocities (tissue Doppler) return to normal within one month after device closure.⁴⁷ In older patients, however, with abnormal relaxation myocardial velocities seem to be volume independent and do not change after device closure, suggesting altered myocardial structure and function.⁴⁷ CMR and MSCT are seldom needed in post-repair follow up (fig 8).

Pulmonary regurgitation (PR)

Isolated clinical PR is a rare problem, but not an innocent one.⁶³ Severe PR is very common after tetralogy of Fallot repair and is associated with RV dysfunction, diminished

Figure 5 Two dimensional transthoracic echocardiogram, left parasternal short axis view. There is RV dilatation and hypertrophy in a young adult patient with an ostium secundum ASD and a Qp/Qs of 3.2. The left ventricle is “squashed” by the dilated RV. LV, left ventricle; RV, right ventricle.

Figure 6 M mode echocardiogram of the same patient shown in fig 5. There is paradoxical septal motion, a sign of RV volume overload. RV enlargement relative to the left ventricle is evident. LV, left ventricle; RV, right ventricle.

Figure 7 Intracardiac echocardiogram of a patient with an ostium secundum ASD just after apposition of an Amplatzer septal occluder umbrella device. The intravascular echocardiographic probe is located in the right atrium. Both sides of the umbrella and its main axis traversing the ASD are clearly visualised. RA, right atrium.

exercise capacity, atrial and ventricular arrhythmias, and sudden death. Timely pulmonary valve replacement may protect patients from PR related complications.^{34 64–69} Therefore, serial quantitative assessment of PR and RV function are key to management. Echocardiography remains the most widely employed imaging modality (fig 9). However, CMR is considered the gold standard for both PR quantification (flow velocity mapping) and RV volumetric analysis (gradient echo)^{18 34 70} (figs 9 and 10). Doppler echocardiography is a useful alternative for semiquantitative PR assessment as a new Doppler index (PR index: ratio of PR duration to diastolic duration) correlates well with the MRI derived pulmonary regurgitant fraction.⁷¹ A PRi less than 0.77 yields 100% sensitivity and 85% specificity for identifying patients with a PR fraction > 24.5%—that is, patients with significant PR.⁷¹ A PR pressure half time < 100 ms has also been found to be a reliable indicator of haemodynamically significant regurgitation.⁷²

Doppler detection of forward and laminar late diastolic pulmonary blood flow, coinciding with atrial systole, present throughout respiration, and associated with a prominent

retrograde superior vena caval flow, defines the so called “restrictive RV physiology”.⁷³ A non-compliant, usually hypertrophied RV, along with low pulmonary arterial diastolic pressures, results in partial presystolic opening of the pulmonary valve during right atrial contraction, which contributes to forward flow (fig 11). This physiology is commonly present early after tetralogy of Fallot repair, where it is associated with a low cardiac output (despite normal biventricular systolic function), leading to longer intensive care stay.^{74 75} In contrast, restrictive RV physiology late after repair of tetralogy counteracts the effects of chronic pulmonary regurgitation and is associated with smaller RV size, shorter QRS duration, and better exercise capacity.^{73 76–80}

Pronounced RV dilatation, especially if serial imaging demonstrates progression, may prompt referral for pulmonary valve replacement before RV dysfunction ensues. Thus, serial follow up of RV volumes—ideally with CMR—is recommended.^{67–69 81 82} Following pulmonary valve replacement, RV volume usually decreases as evidenced by echocardiography,⁸³ radionuclide angiography (RNA),⁸⁴ or CMR.^{68 85} However, there are contradictory reports on RV function^{68 81 85} after pulmonary valve replacement, largely due to different timing of reoperation,^{81 86} different imaging modalities employed and different parameters being measured,^{68 81 86} presence of RV outflow aneurysms or akinesia^{34 86} (fig 12), and variable re-evaluation intervals post-pulmonary valve replacement.^{85 87}

Tricuspid regurgitation (TR)

Congenital TR may be primary, due to a malformed tricuspid valve, as exemplified by isolated tricuspid valve dysplasia or prolapse and Ebstein’s anomaly or Ebstein’s-like anomaly in patients with congenitally corrected transposition (in which case the tricuspid valve represents the systemic atrioventricular valve).⁸⁸ However, it is more frequently secondary, due to severe RV enlargement with resultant tricuspid annular dilatation as happens in patients with RV dysplasia, or free pulmonary regurgitation usually in the context of repaired tetralogy of Fallot.⁸⁸

Ebstein’s anomaly is a complex congenital heart malformation, characterised by an apical displacement of both the septal and the posterior tricuspid leaflets, exceeding 20 mm or 8 mm/m² in adults.⁸⁹ As a consequence, the right heart is divided in three components: the true right atrium, the functional RV, and an intervening zone that is anatomically ventricular but functionally right atrial (atria-

Figure 8 Gradient echo (white blood), magnetic resonance sequence. Four chamber transaxial (short axis of the thorax) view of a patient with an ostium secundum ASD. The defect is clearly seen on the left panel, along with right atrial/ventricular dilatation. On the right panel an Amplatzer septal occluder sealing the defect is seen, along with significant reduction of RV and atrial size six months after defect closure. RA, right atrium; RV, right ventricle.

Figure 9 Left panel: Echocardiographic colour flow mapping (short axis left parasternal view), showing a pulmonary valve regurgitation jet. Right panel: gradient echo (white blood) cardiac magnetic resonance (CMR) sequence of the same patient, four chamber transaxial (short axis of the thorax) view. There is severe right atrioventricular dilatation and RV hypertrophy. Tricuspid regurgitation is depicted as signal void (black coloured jet of blood) at the level of the tricuspid valve towards the right atrium (white arrow). RA, right atrium; RV, right ventricle.

lised RV). The malformation results in moderate to severe TR and may be accompanied by pulmonary stenosis and an ASD with bidirectional shunting, which have a great impact on RV haemodynamics. All these features are adequately assessed with 2D and Doppler echocardiography. When other cardiac lesions are absent (for example, severe pulmonary stenosis), Ebstein's anomaly may be diagnosed in adolescence or adulthood, due to innocent murmurs or arrhythmias, with good long term outcome.⁹⁰ When severe, TR leads to RV volume loading and in the long term RV or biventricular dysfunction. Echocardiography may provide some information regarding the size, shape, and function of the functional RV, however CMR is best suited for a detailed study of the above features.^{91–92}

Surgery should be performed for symptomatic adults.^{93–95} Classical repair of Ebstein's anomaly is usually performed with transverse plication of the atrialised chamber and tricuspid valvoplasty if feasible, or tricuspid valve

replacement.⁹³ However, with severely compromised RV or biventricular function, or in the presence of a relatively hypoplastic and/or malfunctioning RV chamber inadequate to sustain the entire systemic venous return but capable of managing part of the systemic venous return, a one and a half ventricular repair (superior cavopulmonary anastomosis) may provide good functional results.⁹⁶ Therefore a detailed preoperative assessment of RV size and function, but also of the valve leaflet attachments, commissures, and surface is mandatory. The latter cannot be achieved easily with 2D echocardiography; however, newer 3D echocardiographic techniques provide excellent intracardiac views of the valve commissures and leaflets' surface.⁹⁷ We would submit that for a complete evaluation of the right heart anatomy and function, combining echocardiography (2D, 3D, and transoesophageal) with CMR would be the best option in such cases.

In patients with repaired tetralogy of Fallot, TR is related to RV dilatation due to severe PR and possibly valvar trauma

Figure 10 CMR flow velocity mapping of the pulmonary valve. Upper left panel: Forward flow through the valve (traced area) is encoded in white colour. Lower left panel: Backward flow through the pulmonary valve (pulmonary regurgitation) is encoded in black colour. Right panel: Pulmonary flow curve. The area under the curve represents flow. Forward flow is represented by the curve above the reference (zero) line. Backward flow is represented by the curve below the reference line. The last part of the curve above the reference line represents diastolic forward flow through the pulmonary valve, which suggests a restrictive RV. The pulmonary regurgitant fraction (PRF) is calculated as systolic forward flow–diastolic reversal/total flow. In this case the PRF is approximately 50%.

Figure 11 Continuous wave Doppler tracing of the RVOT of a patient with repaired tetralogy of Fallot and severe pulmonary regurgitation. There is residual pulmonary valve stenosis. The pulmonary regurgitation signal ends well before the next systolic signal, which suggests severe pulmonary regurgitation or the existence of a restrictive RV with high RV diastolic pressures, or both. There is a late diastolic signal of forward flow through the pulmonary valve (white arrows), suggesting the existence of a restrictive RV.

during reparative surgery.⁹⁸ When severe it contributes to further RV dilatation.⁹⁸ The existence of significant TR in such patients is considered an indication for pulmonary valve replacement.^{99–100} However, when TR is severe, reoperation is associated with high surgical mortality and poor long term results due to postoperative RV dysfunction.^{100–101} This supports the view that timely pulmonary valve replacement is mandatory before severe TR and RV dysfunction ensue.¹⁰²

THE PRESSURE LOADED RV

Two major models exemplifying pressure loading of the RV will be discussed: RV outflow tract (RVOT) obstruction and the RV supporting the systemic circulation (systemic RV).

Right ventricular outflow tract obstruction–pulmonary stenosis

Isolated stenosis at the valvar level represents 80–90% of pulmonary stenosis cases.^{14–103} However, obstruction may also occur at the subvalvar or supra-valvar level. Regardless of the

Figure 12 Gradient echo (white blood) CMR sequence, sagittal plane (RVOT view), end systole. The RV is severely dilated and hypertrophied. The upper part of the RV chamber, almost of same size with the main RV chamber below, represents a huge RVOT aneurysm. An, aneurysm; RV, right ventricle.

Figure 13 Continuous wave Doppler tracing of the RVOT in a patient with combined pulmonary valve stenosis and regurgitation. Note that the signal of pulmonary regurgitation (above the zero line) ends well before the next systolic Doppler wave (below the line). This may be either due to severe pulmonary regurgitation, or to elevated RV diastolic pressure.

level of obstruction, the RV exerts a hypertrophic response the degree of which varies with the magnitude of obstruction.¹⁰⁴ Echocardiography is the diagnostic method of choice.¹⁰³ Continuous wave Doppler is used for estimation of the pressure gradient across the RVOT¹⁴ (fig 13). In contrast to left sided stenoses, the RVOT instantaneous gradient correlates well with catheter based peak-to-peak gradient, obviating the need for cardiac catheterisation.¹⁰⁵ The latter is saved for patients with long RVOT stenoses at the infundibular level where Doppler may be inaccurate. More sophisticated methods, mainly CMR, may be needed for detailed imaging of the RVOT and for assessment of RV size and function¹⁰³ (fig 14). This need is exemplified by more complex anomalies like the “double chambered RV”.¹⁰⁶ The latter is a term used for anomalous muscle bundles that divide the RV into a high pressure apical chamber and a low pressure outlet/infundibular chamber^{14–106} (fig 15).

The systemic right ventricle

In terms of physiology the RV is teleologically well suited for the changes in preload that normally occur with changes in intrathoracic pressure and systemic venous return and poorly tolerant of acute changes in afterload.¹³ Fundamental anatomic and physiologic principles pose obvious disadvantages to the RV supporting the systemic circulation.

Figure 14 Spin echo (black blood) CMR sequence, sagittal plane (RVOT view), end systole. There is severe RV hypertrophy. The pulmonary valve is thickened and domed. The main pulmonary artery is severely dilated. PA, pulmonary artery; RV, right ventricle.

Figure 15 Left panel: Gradient echo (white blood) CMR sequence, oblique sagittal plane (short axis of the ventricles), end systole. The RV is divided into two chambers by a thick ring of ventricular myocardium. This anomaly is called "double chambered RV". Right panel: Echocardiographic colour flow mapping (short axis left parasternal view) of the same patient shown on the left. There is blood turbulence (aliasing) within the RV at the level of the hypertrophic muscle bands. LV, left ventricle; RV, right ventricle.

Figure 16 Gradient echo (white blood) CMR sequences. (A) Sagittal plane, normal cardiac anatomy. The left atrium is draining into the left ventricle, which is connected to the aorta. (B–D) Various CMR views of a patient with complete transposition of the great arteries and Mustard repair (atrial switch). (B) Sagittal plane. The left ventricle is connected to the pulmonary artery (subpulmonary left ventricle). The RV is connected to the aorta (systemic RV). The systemic RV is dilated and severely hypertrophied. (C) Four chamber view. The pulmonary venous pathway of the atrial switch is shown. The pulmonary veins (left lower pulmonary vein is clearly seen in this level) are draining into the right atrium through the baffle (arrow). The systemic RV is dilated and severely hypertrophied. (D) Coronal view. The systemic venous pathway of the atrial switch is shown. The inferior and superior vena cavae (arrows) are directed underneath the baffle to the left atrium. Ao, aorta; LA, left atrium; LV, left ventricle; PA, pulmonary artery; RV, right ventricle.

Figure 17 Gradient echo (white blood) CMR sequence, oblique sagittal (short axis of the ventricles view) of a patient with complete transposition of the great arteries and Senning (atrial switch) repair. The RV is severely hypertrophied and dilated. The interventricular septum is bowing towards the left ventricle. LV, left ventricle; RV, right ventricle.

Figure 18 Magnetic resonance angiography (MRA) with gadolinium injection through a peripheral vein. Ventriculography, frontal projection. The chamber opacified demonstrates left ventricular characteristics (conical shape, smooth walls); however, it is connected to the pulmonary arteries, which are also opacified by gadolinium. This represents a subpulmonary left ventricle in a patient with complete transposition of the great arteries and Mustard repair (atrial switch). MRA allows for a detailed non-invasive assessment of the ventriculo-arterial connections and of the anatomy of the great vessels.

Figure 19 Left panel: Gradient echo sequence (white blood), short axis view of the RV and the pulmonary venous pathway in a patient with complete transposition of the great arteries and Mustard repair (atrial switch). The RV is dilated and hypertrophied. There is a signal void (black coloured jet) at the level of the tricuspid valve caused by tricuspid regurgitation. The pulmonary venous return finds its way back to the RV through a baffle (black arrow), which redirects blood from the pulmonary veins (white arrow) to the left atrium (LA). The RV is connected to the aorta (not shown) and supports the systemic circulation. The left ventricle is elongated and thin walled, and supports the pulmonary circulation. Right panel: The same patient imaged with a late gadolinium enhancement CMR sequence. Gadolinium is washed out from normal myocardium, which appears grey-black. Areas of necrosis and scarring demonstrate late gadolinium enhancement (white colour). There is gadolinium enhancement of an area of the RV free wall (black arrow), suggesting myocardial scarring. LA, left atrium; LV, left ventricle; RV, right ventricle.

Atrial switch operations (Mustard and Senning)

Complete transposition of the great arteries is incompatible with life without a surgical switch of the circulation either at atrial or great arterial level (physiologic or anatomic repair respectively). The former procedures are the Mustard and Senning operations, which have been performed for over 40 years now and have transformed the outlook for these patients¹⁰⁷ (figs 16–19). However, the atrial switch procedures result in the RV supporting the systemic circulation. Long term concerns remain: the prospect of RV failure, arrhythmias (atrial flutter variants and sick sinus syndrome), and accordingly compromised long term quality of life and survival for many of these patients. Assessment of RV function is paramount but also challenging, because of the inherent problems in assessing RV function (discussed above) and the absence of criteria for “normal” values.¹⁰⁸ Volumetric methods (echocardiography, RNA, CMR) have been the mainstay of RV assessment.¹⁰⁸ Cumulative survival 25–30 years after the Mustard repair is as high as 80%. However, it seems that there is progressive deterioration of RV function with time in most patients after the Mustard repair and this is often accompanied by significant systemic atrioventricular valve (tricuspid) regurgitation¹⁰⁹ (fig 19). This decline in RV function along with residual lesions (baffle obstruction or leakage, residual ventricular septal defect, and pulmonary valve stenosis), contribute to late morbidity and mortality manifested as reduced exercise capacity, heart failure, endocarditis, supraventricular arrhythmia, reoperation, and cardiac death.¹⁰⁹

The cause of RV dysfunction is unclear, however. Myocardial perfusion defects¹¹⁰ and impaired myocardial flow reserve in the systemic RV have been demonstrated in survivors of the Mustard operation, suggesting inadequate coronary blood supply.¹¹¹ The cause of these perfusion defects, however, is not classic coronary artery disease. It is more likely that they represent a supply/demand ischaemia in the context of severe RV hypertrophic response to systemic pressure loading.¹¹² Post-ejection RV longitudinal shortening (longitudinal excursion following the ejection phase), during stress echocardiography was shown in a significant number of patients,¹¹³ suggesting incoordinated myocardial contraction, highly sensitive to myocardial ischemia.¹¹³ Regions of

abnormal RV myocardium can be visualised late after atrial switch with the use of CMR with late gadolinium enhancement and are likely to represent focal fibrosis³⁹ (fig 19). The presence and extent of such regions correlate with RV mass, RV dilatation, and impaired systolic function, suggesting that hypertrophy is associated with fibrosis in some patients, and correlates inversely with RV systolic performance.³⁹ Furthermore, gadolinium enhancement was associated with markers of adverse outcome like QRS duration and arrhythmia itself, underlining the prognostic significance of these findings.³⁹

Although accurate assessment of RV ejection fraction is important, the definition of “normal” systemic RV ejection fraction remains problematic and depends on the method of determination. However, most authorities agree that a systemic RV ejection fraction > 50% can be considered normal (in the absence of significant valve regurgitation).^{114–115} For the reasons discussed, CMR is considered the gold standard for the study of RV size and function in these patients.¹¹⁵ Radionuclide angiography is a useful alternative for serial follow up when CMR or CT are not available.^{114–116} Although transthoracic echo assessment of adult patients is limited in quantitative volumetric data, it provides invaluable information on baffle patency, leaks (with contrast studies), valvar regurgitation or stenosis and, in experienced hands, semiquantitative information on RV function.¹¹⁷ MRI derived RV volumes correlate positively with echo derived RV inlet dimensions and negatively with the dp/dt of the tricuspid regurgitant jet (indirect measure of RV contractile function).¹¹⁷ Furthermore, RV longitudinal function (M mode: wall excursion measured from the apex) correlates with CMR derived RV ejection fraction.¹¹⁷

Echocardiographic indices of systemic RV function during dobutamine stress (such as RV long axis excursion) predict exercise capacity, establishing stress echocardiography as an important semi-invasive, physiologic imaging modality.¹¹³ Sinus node dysfunction is a relatively frequent finding in these patients, necessitating permanent pacing.¹¹⁸ Pacing, in turn, constitutes a contraindication for CMR at present. Other emerging imaging modalities, namely MSCT, may prove to be useful alternatives for volumetric analysis of the RV.¹¹⁹

Figure 20 Gradient echo (white blood) CMR sequences of a patient with corrected transposition of the great arteries (double discordance). Left panel: Transaxial four chamber view. The pulmonary veins (left and right lower veins in this plane) are draining to the left atrium, which is however connected to the RV (systemic RV). The right atrium, in turn, is connected to the left ventricle (subpulmonary LV). Right panel: Same patient shown on the left. The relationships of the dilated and hypertrophied RV with the aorta and the left atrium are depicted. There is a signal void of tricuspid valve (systemic atrioventricular valve) regurgitation and a signal void of aortic regurgitation. Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

Congenitally corrected transposition of the great arteries (ccTGA)

The RV supports the systemic circulation in patients with ccTGA. Associated lesions (ventricular septal defect, pulmonary stenosis, and Ebstein's anomaly of the systemic tricuspid valve) are common.¹²⁰ Diagnosis may be made in adult life in non-cyanotic patients, usually by identifying a systemic ventricle with RV morphologic characteristics¹²¹ (coarse trabeculations, moderator band, and the insertion of the septal leaflet of a morphologically tricuspid valve to the ventricular septum in conjunction with a morphologically mitral valve on the right side).¹²¹ The relation of the two ventricles (and the two great arteries) is more side by side than the usual anteroposterior, rendering the apical and subxiphoid four chamber the most useful echocardiographic views for diagnosis. Transoesophageal echocardiography may be required and, as with complete TGA, additional imaging such as CMR is preferable for assessing systemic RV function¹²² (fig 20).

Long term outcome is not normal even in patients without associated lesions due to a propensity to complete heart block,¹²³ tricuspid valve regurgitation (TR),¹²⁴ and the development of RV systolic dysfunction.^{125–130} Not surprisingly, more than moderate TR and RV dysfunction are significantly related to increased mortality,¹²⁹ with TR being the most significant independent predictor of outcome.¹³⁰ However, TR strongly relates to RV dysfunction, raising the question whether TR leads to RV dysfunction or vice versa.^{128–130} Despite difficulties in assessing the systemic RV in ccTGA, usually a semiquantitative evaluation of ventricular function and TR by echo is feasible. In contrast to patients with atrioventricular concordance, who often tolerate a significant degree of mitral insufficiency for decades before left ventricular failure ensues, RV dysfunction usually starts within five years from onset of TR in ccTGA patients (without associated lesions or surgery).^{130–132} RV failure with ventricular enlargement results in worsening of TR due to annular dilatation. The factors responsible for accelerated failure of the systemic RV are not quite clear. It seems that ventricular geometry and the design of the respective atrioventricular valve is important.¹³³ Also perfusion defects at rest have been reported in patients with ccTGA without associated lesions.^{134–135} Coronary flow reserve assessed with positron

emission tomography is decreased, indicating altered vasoreactivity and quantitative changes in microcirculation.¹³⁶

The adverse interplay between TR and RV dysfunction in these patients calls for timely tricuspid valve replacement (repair does not work), otherwise patients should be considered for transplantation.^{130–137} In this regard, serial assessment of TR and RV function is mandatory, underscoring the benefits of a combined imaging approach with echo and CMR.^{4–20–138–139} Gated equilibrium radionuclide angiocardiology may also be used for assessment of RV function at rest and during exercise.¹²⁶ Coronary artery origin and distribution are reversed and frequently anomalous in these patients and non-invasive coronary angiography (with CT or CMR) can delineate it.^{2–3–140}

CONCLUSION

The RV, with its complex geometry and unique adaptive mechanisms in CHD, remains a challenge to the cardiologist. The RV is a pivotal chamber and its dysfunction—both systolic and diastolic—has clear implications to short and long term outcome. Recent advances in imaging, particularly in CMR, have revolutionised the exploration of RV anatomy and function and have shed light on late pathophysiology of many CHD defects. Transthoracic echocardiography remains the workhorse of non-invasive assessment of the RV in patients with CHD, however. Combined with other imaging, appropriately selected and timed for the individual patient with CHD, echocardiography remains key to assessing disease progression and timing of late re-intervention.

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Authors' affiliations

P A Davlouros, M A Gatzoulis, Adult Congenital Heart Centre & Centre for Pulmonary Hypertension, Royal Brompton & Harefield NHS Trust, National Heart and Lung Institute, Imperial College, London, UK
P A Davlouros, Congenital Heart Programme, Cardiology Division, Patras University Hospital, Rion, Patras, Greece

K Niwa, Adult Congenital Heart Disease Programme, Chiba Cardiovascular Center, Chiba, Japan

G Webb, Philadelphia Adult Congenital Heart Center, University of Pennsylvania, Philadelphia, USA

Correspondence to: Dr Periklis A Davlouros, Patras University Hospital, Rion, 26500, Patras, Greece; pdav@otenet.gr

REFERENCES

- Dini FL, Galderisi M, Mondillo S, et al. [The right ventricle: role of Doppler echocardiography in clinical practice]. *Ital Heart J Suppl* 2004;5:757-69.
- Samyn MM. A review of the complementary information available with cardiac magnetic resonance imaging and multi-slice computed tomography (CT) during the study of congenital heart disease. *Int J Cardiovasc Imaging* 2004;20:569-78.
- Boxt LM. Magnetic resonance and computed tomographic evaluation of congenital heart disease. *J Magn Reson Imaging* 2004;19:827-47.
- Pignatelli RH, McMahon CJ, Chung T, et al. Role of echocardiography versus MRI for the diagnosis of congenital heart disease. *Curr Opin Cardiol* 2003;18:357-65.
- Friedberg MK, Rosenthal DN. New developments in echocardiographic methods to assess right ventricular function in congenital heart disease. *Curr Opin Cardiol* 2005;20:84-8.
- Raman SV, Cook SC, McCarthy B, et al. Usefulness of multidetector row computed tomography to quantify right ventricular size and function in adults with either tetralogy of Fallot or transposition of the great arteries. *Am J Cardiol* 2005;95:683-6.
- Gatzoulis MA, Hechter S, Siu SC, et al. Outpatient clinics for adults with congenital heart disease: increasing workload and evolving patterns of referral. *Heart* 1999;81:57-61.
- Niwa K, Perloff JK, Webb GD, et al. Survey of specialized tertiary care facilities for adults with congenital heart disease. *Int J Cardiol* 2004;96:211-6.
- Therrien J, Dore A, Gersony W, et al. CCS Consensus Conference 2001 update: recommendations for the management of adults with congenital heart disease. Part I. *Can J Cardiol* 2001;17:940-59.
- Therrien J, Gatzoulis M, Graham T, et al. Canadian Cardiovascular Society Consensus Conference 2001 update: recommendations for the management of adults with congenital heart disease. Part II. *Can J Cardiol* 2001;17:1029-50.
- Therrien J, Warnes C, Daliento L, et al. Canadian Cardiovascular Society Consensus Conference 2001 update: recommendations for the management of adults with congenital heart disease. Part III. *Can J Cardiol* 2001;17:1135-58.
- Rumberger JA, Behrenbeck T, Bell MR, et al. Determination of ventricular ejection fraction: a comparison of available imaging methods. The cardiovascular imaging working group. *Mayo Clin Proc* 1997;72:860-70.
- Kvasnicka J, Vokrouhlicky L. Heterogeneity of the myocardium. Function of the left and right ventricle under normal and pathological conditions. *Physiol Res* 1991;40:31-7.
- Valdes-Cruz LM, Cayre RO. Anomalies of the right ventricular outflow tract and pulmonary arteries. In: Valdes-Cruz LM, Cayre RO, eds. *Echocardiographic diagnosis of congenital heart disease. An embryologic and anatomic approach*. Philadelphia: Lippincott-Raven 1999:325-48.
- Yacoub MH. The case for anatomic correction of transposition of the great arteries. *J Thorac Cardiovasc Surg* 1979;78:3-6.
- Yacoub MH. Two hearts that beat as one. *Circulation* 1995;92:156-7.
- Vogel M, White PA, Redington AN. In vitro validation of right ventricular volume measurement by three dimensional echocardiography. *Br Heart J* 1995;74:460-3.
- Helbing WA, Rebergen SA, Maliopaard C, et al. Quantification of right ventricular function with magnetic resonance imaging in children with normal hearts and with congenital heart disease. *Am Heart J* 1995;130:828-37.
- Vogel M, Gutberlet M, Dittich S, et al. Comparison of transthoracic three dimensional echocardiography with magnetic resonance imaging in the assessment of right ventricular volume and mass. *Heart* 1997;78:127-30.
- Rebergen SA, de Roos A. Congenital heart disease. Evaluation of anatomy and function by MRI. *Herz* 2000;25:365-83.
- Olivier M, O'Leary PW, Pankratz VS, et al. Serial Doppler assessment of diastolic function before and after the Fontan operation. *J Am Soc Echocardiogr* 2003;16:1136-43.
- Bolca O, Hobikoglu G, Norgaz T, et al. [The prediction of pulmonary artery systolic pressure and vascular resistance by using tricuspid annular tissue Doppler imaging]. *Anadolu Kardiyol Derg* 2002;2:302-6.
- Watanabe M, Ono S, Tomomasa T, et al. Measurement of tricuspid annular diastolic velocities by Doppler tissue imaging to assess right ventricular function in patients with congenital heart disease. *Pediatr Cardiol* 2003;24:463-7.
- Tei C, Ling LH, Hodge DO, et al. New index of combined systolic and diastolic myocardial performance: a simple and reproducible measure of cardiac function—a study in normals and dilated cardiomyopathy. *J Cardiol* 1995;26:357-66.
- Eidem BW, O'Leary PW, Tei C, et al. Usefulness of the myocardial performance index for assessing right ventricular function in congenital heart disease. *Am J Cardiol* 2000;86:654-8.
- Vogel M, Schmidt MR, Kristiansen SB, et al. Validation of myocardial acceleration during isovolumic contraction as a novel noninvasive index of right ventricular contractility: comparison with ventricular pressure-volume relations in an animal model. *Circulation* 2002;105:1693-9.
- Toyono M, Harada K, Tamura M, et al. Myocardial acceleration during isovolumic contraction as a new index of right ventricular contractile function and its relation to pulmonary regurgitation in patients after repair of tetralogy of Fallot. *J Am Soc Echocardiogr* 2004;17:332-7.
- Vogel M, Derrick G, White PA, et al. Systemic ventricular function in patients with transposition of the great arteries after atrial repair: a tissue Doppler and conductance catheter study. *J Am Coll Cardiol* 2004;43:100-6.
- Miller D, Farah MG, Liner A, et al. The relation between quantitative right ventricular ejection fraction and indices of tricuspid annular motion and myocardial performance. *J Am Soc Echocardiogr* 2004;17:443-7.
- Ishii M, Eto G, Tei C, et al. Quantitation of the global right ventricular function in children with normal heart and congenital heart disease: a right ventricular myocardial performance index. *Pediatr Cardiol* 2000;21:416-21.
- Masani ND. Transoesophageal echocardiography in adult congenital heart disease. *Heart* 2001;86(suppl II):ii30-40.
- Zaret BL, Wackers FJ. Nuclear cardiology (2). *N Engl J Med* 1993;329:855-63.
- Baker E. Radionuclide investigation of congenital heart disease. *Heart* 2000;84:467-8.
- Davlouros PA, Kilner PJ, Hornung TS, et al. Right ventricular function in adults with repaired tetralogy of Fallot assessed with cardiovascular magnetic resonance imaging: detrimental role of right ventricular outflow aneurysms or akinesia and adverse right-to-left ventricular interaction. *J Am Coll Cardiol* 2002;40:2044-52.
- Babu-Narayan SV, Kilner PJ, Gatzoulis MA. When to order cardiovascular magnetic resonance in adults with congenital heart disease. *Curr Cardiol Rep* 2003;5:324-30.
- Prasad SK, Soukias N, Hornung T, et al. Role of magnetic resonance angiography in the diagnosis of major aortopulmonary collateral arteries and partial anomalous pulmonary venous drainage. *Circulation* 2004;109:207-14.
- McCrohon JA, Moon JC, Prasad SK, et al. Differentiation of heart failure related to dilated cardiomyopathy and coronary artery disease using gadolinium-enhanced cardiovascular magnetic resonance. *Circulation* 2003;108:54-9.
- Moon JC, Reed E, Sheppard MN, et al. The histologic basis of late gadolinium enhancement cardiovascular magnetic resonance in hypertrophic cardiomyopathy. *J Am Coll Cardiol* 2004;43:2260-4.
- Babu-Narayan SV, Goktekin O, Moon JC, et al. Late gadolinium enhancement cardiovascular magnetic resonance of the systemic right ventricle in adults with previous atrial redirection surgery for transposition of the great arteries. *Circulation* 2005;111:2091-8.
- Rigby ML. Atrial septal defect. In: Gatzoulis M, Webb G, Daubeney P, eds. *Diagnosis and management of adult congenital heart disease*. Philadelphia: Churchill Livingstone, 2003:163-70.
- Valdes-Cruz LM, Cayre RO. Atrial septal defects. In: Valdes-Cruz LM, Cayre RO, eds. *Echocardiographic diagnosis of congenital heart disease. An embryologic and anatomic approach*. Philadelphia: Lippincott-Raven, 1999:187-98.
- Swan L, Gatzoulis MA. Closure of atrial septal defects: is the debate over? *Eur Heart J* 2003;24:130-2.
- Popio KA, Gorlin R, Teichholz LE, et al. Abnormalities of left ventricular function and geometry in adults with an atrial septal defect. Ventriculographic, hemodynamic and echocardiographic studies. *Am J Cardiol* 1975;36:302-8.
- Vincent RN, Saurette RH, Pelech AN, et al. Interventricular septal motion and left ventricular function in patients with atrial septal defect. *Pediatr Cardiol* 1988;9:143-8.
- Baker EJ, Shubao C, Clarke SE, et al. Radionuclide measurement of right ventricular function in atrial septal defect, ventricular septal defect and complete transposition of the great arteries. *Am J Cardiol* 1986;57:1142-6.
- Berger F, Jin Z, Ishihashi K, et al. Comparison of acute effects on right ventricular haemodynamics of surgical versus interventional closure of atrial septal defects. *Cardiol Young* 1999;9:484-7.
- Pascotto M, Caso P, Santoro G, et al. Analysis of right ventricular Doppler tissue imaging and load dependence in patients undergoing percutaneous closure of atrial septal defect. *Am J Cardiol* 2004;94:1202-5.
- Murphy JG, Gersh BJ, McGoon MD, et al. Long-term outcome after surgical repair of isolated atrial septal defect. Follow-up at 27 to 32 years. *N Engl J Med* 1990;323:1645-50.
- Attie F, Rosas M, Granados N, et al. Surgical treatment for secundum atrial septal defects in patients >40 years old. A randomized clinical trial. *J Am Coll Cardiol* 2001;38:2035-42.
- Konstantinides S, Geibel A, Olschewski M, et al. A comparison of surgical and medical therapy for atrial septal defect in adults. *N Engl J Med* 1995;333:469-73.
- Gatzoulis MA, Redington AN, Somerville J, et al. Should atrial septal defects in adults be closed? *Ann Thorac Surg* 1996;61:657-9.
- Popelova J, Hlavacek K, Honek T, et al. Atrial septal defect in adults. *Can J Cardiol* 1996;12:983-8.
- Gatzoulis MA, Freeman MA, Siu SC, et al. Atrial arrhythmia after surgical closure of atrial septal defects in adults. *N Engl J Med* 1999;340:839-46.
- Kort HW, Balzer DT, Johnson MC. Resolution of right heart enlargement after closure of secundum atrial septal defect with transcatheter technique. *J Am Coll Cardiol* 2001;38:1528-32.
- Thanopoulos BD, Laskari CV, Tsaousis GS, et al. Closure of atrial septal defects with the Amplatzer occlusion device: preliminary results. *J Am Coll Cardiol* 1998;31:1110-6.

- 56 Mullen MJ, Dias BF, Walker F, et al. Intracardiac echocardiography guided device closure of atrial septal defects. *J Am Coll Cardiol* 2003;**41**:285–92.
- 57 Du ZD, Hijazi ZM, Kleinman CS, et al. Comparison between transcatheter and surgical closure of secundum atrial septal defect in children and adults: results of a multicenter nonrandomized trial. *J Am Coll Cardiol* 2002;**39**:1836–44.
- 58 Brochu MC, Baril JF, Dore A, et al. Improvement in exercise capacity in asymptomatic and mildly symptomatic adults after atrial septal defect percutaneous closure. *Circulation* 2002;**106**:1821–6.
- 59 Bjorkhem G, Lundstrom NR. Echocardiographic studies of children operated on for congenital heart disease; evaluation during the first postoperative year. *Eur J Cardiol* 1980;**11**:33–50.
- 60 Meyer RA, Korfhagen JC, Covitz W, et al. Long-term follow-up study after closure of secundum atrial septal defect in children: an echocardiographic study. *Am J Cardiol* 1982;**50**:143–8.
- 61 Schussler JM, Anwar A, Phillips SD, et al. Effect on right ventricular volume of percutaneous Amplatzer closure of atrial septal defect in adults. *Am J Cardiol* 2005;**95**:993–5.
- 62 Santoro G, Paschetto M, Sarubbi B, et al. Early electrical and geometric changes after percutaneous closure of large atrial septal defect. *Am J Cardiol* 2004;**93**:876–80.
- 63 Shimazaki Y, Blackstone EH, Kirklin JW. The natural history of isolated congenital pulmonary valve incompetence: surgical implications. *Thorac Cardiovasc Surg* 1984;**32**:257–9.
- 64 Gatzoulis MA, Till JA, Redington AN. Depolarization-repolarization inhomogeneity after repair of tetralogy of Fallot. The substrate for malignant ventricular tachycardia? *Circulation* 1997;**95**:401–4.
- 65 Abd El Rahman MY, Abdul-Khaliq H, Vogel M, et al. Relation between right ventricular enlargement, QRS duration, and right ventricular function in patients with tetralogy of Fallot and pulmonary regurgitation after surgical repair. *Heart* 2000;**84**:416–20.
- 66 Gatzoulis MA, Balaji S, Webber SA, et al. Risk factors for arrhythmia and sudden cardiac death late after repair of tetralogy of Fallot: a multicentre study. *Lancet* 2000;**356**:975–81.
- 67 Therrien J, Siu SC, Harris L, et al. Impact of pulmonary valve replacement on arrhythmia propensity late after repair of tetralogy of Fallot. *Circulation* 2001;**103**:2489–94.
- 68 Vliegen HW, van Straten A, de Roos A, et al. Magnetic resonance imaging to assess the hemodynamic effects of pulmonary valve replacement in adults late after repair of tetralogy of Fallot. *Circulation* 2002;**106**:1703–7.
- 69 van Straten A, Vliegen HW, Hazekamp MG, et al. Right ventricular function after pulmonary valve replacement in patients with tetralogy of Fallot. *Radiology* 2004;**233**:824–9.
- 70 van Straten A, Vliegen HW, Hazekamp MG, et al. Right ventricular function late after total repair of tetralogy of Fallot. *Eur Radiol* 2005;**15**:702–7.
- 71 Li W, Davlouros PA, Kilner PJ, et al. Doppler-echocardiographic assessment of pulmonary regurgitation in adults with repaired tetralogy of Fallot: comparison with cardiovascular magnetic resonance imaging. *Am Heart J* 2004;**147**:165–72.
- 72 Silversides CK, Veldtman GR, Crossin J, et al. Pressure half-time predicts hemodynamically significant pulmonary regurgitation in adult patients with repaired tetralogy of Fallot. *J Am Soc Echocardiogr* 2003;**16**:1057–62.
- 73 Gatzoulis MA, Clark AL, Cullen S, et al. Right ventricular diastolic function 15 to 35 years after repair of tetralogy of Fallot. Restrictive physiology predicts superior exercise performance. *Circulation* 1995;**91**:1775–81.
- 74 Cullen S, Shore D, Redington A. Characterization of right ventricular diastolic performance after complete repair of tetralogy of Fallot. Restrictive physiology predicts slow postoperative recovery. *Circulation* 1995;**91**:1782–9.
- 75 Rathore KS, Gupta N, Kapoor A, et al. Assessment of right ventricular diastolic function: does it predict post-operative course in tetralogy of Fallot. *Indian Heart J* 2004;**56**:220–4.
- 76 Gatzoulis MA, Till JA, Somerville J, et al. Mechano-electrical interaction in tetralogy of Fallot. QRS prolongation relates to right ventricular size and predicts malignant ventricular arrhythmias and sudden death. *Circulation* 1995;**92**:231–7.
- 77 Norgard G, Gatzoulis MA, Moraes F, et al. Relationship between type of outflow tract repair and postoperative right ventricular diastolic physiology in tetralogy of Fallot. Implications for long-term outcome. *Circulation* 1996;**94**:3276–80.
- 78 Eroglu AG, Sarioglu A, Sarioglu T. Right ventricular diastolic function after repair of tetralogy of Fallot: its relationship to the insertion of a 'transannular' patch. *Cardiol Young* 1999;**9**:384–91.
- 79 Munkhammar P, Cullen S, Jogi P, et al. Early age at repair prevents restrictive right ventricular (RV) physiology after surgery for tetralogy of Fallot (TOF): diastolic RV function after TOF repair in infancy. *J Am Coll Cardiol* 1998;**32**:1083–7.
- 80 Norgard G, Gatzoulis MA, Josen M, et al. Does restrictive right ventricular physiology in the early postoperative period predict subsequent right ventricular restriction after repair of tetralogy of Fallot? *Heart* 1998;**79**:481–4.
- 81 Therrien J, Siu SC, McLaughlin PR, et al. Pulmonary valve replacement in adults late after repair of tetralogy of Fallot: are we operating too late? *J Am Coll Cardiol* 2000;**36**:1670–5.
- 82 Therrien J, Provost Y, Merchant N, et al. Optimal timing for pulmonary valve replacement in adults after tetralogy of Fallot repair. *Am J Cardiol* 2005;**95**:779–82.
- 83 Disciglio B, Dearani JA, Puga FJ, et al. Late pulmonary valve replacement after repair of tetralogy of Fallot. *J Thorac Cardiovasc Surg* 2001;**121**:344–51.
- 84 d'Udekem Y, Rubay J, Shango-Lody P, et al. Late homograft valve insertion after transannular patch repair of tetralogy of Fallot. *J Heart Valve Dis* 1998;**7**:450–4.
- 85 van Huysduynen BH, van Straten A, Swenne CA, et al. Reduction of QRS duration after pulmonary valve replacement in adult Fallot patients is related to reduction of right ventricular volume. *Eur Heart J* 2005;**26**:928–32.
- 86 d'Udekem Y, Rubay J, Ovaert C. Failure of right ventricular recovery of Fallot patients after pulmonary valve replacement: delay of reoperation or surgical technique? *J Am Coll Cardiol* 2001;**37**:2008–9.
- 87 Stephenson EA, Redington AN. Reduction of QRS duration following pulmonary valve replacement in tetralogy of Fallot: implications for arrhythmia reduction? *Eur Heart J* 2005;**26**:863–4.
- 88 Ammass NM, Warnes CA, Connolly HM, et al. Mimics of Ebstein's anomaly. *Am Heart J* 1997;**134**:508–13.
- 89 Oechslin E, Buchholz S, Jenni R. Ebstein's anomaly in adults: Doppler-echocardiographic evaluation. *Thorac Cardiovasc Surg* 2000;**48**:209–13.
- 90 Celemajer DS, Bull C, Till JA, et al. Ebstein's anomaly: presentation and outcome from fetus to adult. *J Am Coll Cardiol* 1994;**23**:170–6.
- 91 Nihoyannopoulos P, McKenna WJ, Smith G, et al. Echocardiographic assessment of the right ventricle in Ebstein's anomaly: relation to clinical outcome. *J Am Coll Cardiol* 1986;**8**:627–35.
- 92 Gutberlet M, Oellinger H, Ewert P, et al. [Pre- and postoperative evaluation of ventricular function, muscle mass and valve morphology by magnetic resonance tomography in Ebstein's anomaly]. *Rofo* 2000;**172**:436–42.
- 93 Chauvaud S, Berrebi A, d'Attellis N, et al. Ebstein's anomaly: repair based on functional analysis. *Eur J Cardiothorac Surg* 2003;**23**:525–31.
- 94 Di Russo GB, Gaynor JW. Ebstein's anomaly: Indications for repair and surgical technique. *Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu* 1999;**2**:35–50.
- 95 Mair DD, Seward JB, Driscoll DJ, et al. Surgical repair of Ebstein's anomaly: selection of patients and early and late operative results. *Circulation* 1985;**72**:1170–6.
- 96 Corno AF, Chassot PG, Payot M, et al. Ebstein's anomaly: one and a half ventricular repair. *Swiss Med Wkly* 2002;**132**:485–8.
- 97 Taktak A, Acar P, Dulac Y, et al. [A new approach to the tricuspid valve in Ebstein's anomaly by real time 3D echocardiography]. *Arch Mal Coeur Vaiss* 2005;**98**:531–7.
- 98 Mahle WT, Parks WJ, Fyfe DA, et al. Tricuspid regurgitation in patients with repaired Tetralogy of Fallot and its relation to right ventricular dilatation. *Am J Cardiol* 2003;**92**:643–5.
- 99 Misbach GA, Turley K, Ebert PA. Pulmonary valve replacement for regurgitation after repair of tetralogy of Fallot. *Ann Thorac Surg* 1983;**36**:684–91.
- 100 Conte S, Jashari R, Eyskens B, et al. Homograft valve insertion for pulmonary regurgitation late after valveless repair of right ventricular outflow tract obstruction. *Eur J Cardiothorac Surg* 1999;**15**:143–9.
- 101 Hachiro Y, Takagi N, Koyanagi T, et al. Reoperation for tricuspid regurgitation after total correction of tetralogy of Fallot. *Ann Thorac Cardiovasc Surg* 2002;**8**:199–203.
- 102 Davlouros PA, Karatza AA, Gatzoulis MA, et al. Timing and type of surgery for severe pulmonary regurgitation after repair of tetralogy of Fallot. *Int J Cardiol* 2004;**97**(suppl 1):91–101.
- 103 Dore A. Pulmonary stenosis. In: Gatzoulis M, Webb G, Daubeney P, eds. *Diagnosis and management of adult congenital heart disease*. Philadelphia: Churchill Livingstone, 2003:299–303.
- 104 Graham TP Jr. Ventricular performance in congenital heart disease. *Circulation* 1991;**84**:2259–74.
- 105 Currie PJ, Hagler DJ, Seward JB, et al. Instantaneous pressure gradient: a simultaneous Doppler and dual catheter correlative study. *J Am Coll Cardiol* 1986;**7**:800–6.
- 106 Doff B, McElhinney A, Goldmuntz E. Double-chambered right ventricle. In: Gatzoulis M, Webb G, Daubeney P, eds. *Diagnosis and management of adult congenital heart disease*. Philadelphia: Churchill Livingstone, 2003:305–11.
- 107 Mustard WT. Recent experiences with surgical management of transposition of the great arteries. *J Cardiovasc Surg (Torino)* 1968;**9**:532–6.
- 108 Derrick G, Deanfield JE. Decline in ventricular function and clinical condition after Mustard repair. *Eur Heart J* 2004;**25**:1863–4.
- 109 Roos-Hesselink JW, Meijboom FJ, Spitaels SE, et al. Decline in ventricular function and clinical condition after Mustard repair for transposition of the great arteries (a prospective study of 22–29 years). *Eur Heart J* 2004;**25**:1264–70.
- 110 Millane T, Bernard EJ, Jaeggi E, et al. Role of ischemia and infarction in late right ventricular dysfunction after atrial repair of transposition of the great arteries. *J Am Coll Cardiol* 2000;**35**:1661–8.
- 111 Singh TP, Humes RA, Muzik O, et al. Myocardial flow reserve in patients with a systemic right ventricle after atrial switch repair. *J Am Coll Cardiol* 2001;**37**:2120–5.
- 112 Hornung TS, Kilner PJ, Davlouros PA, et al. Excessive right ventricular hypertrophic response in adults with the mustard procedure for transposition of the great arteries. *Am J Cardiol* 2002;**90**:800–3.
- 113 Li W, Hornung TS, Francis DP, et al. Relation of biventricular function quantified by stress echocardiography to cardiopulmonary exercise capacity in adults with Mustard (atrial switch) procedure for transposition of the great arteries. *Circulation* 2004;**110**:1380–6.
- 114 Hurwitz RA, Caldwell RL, Girod DA, et al. Right ventricular systolic function in adolescents and young adults after Mustard operation for transposition of the great arteries. *Am J Cardiol* 1996;**77**:294–7.
- 115 Hornung TS, Derrick GP, Deanfield JE, et al. Transposition complexes in the adult: a changing perspective. *Cardiol Clin* 2002;**20**:405–20.

- 116 **Hornung TS**, Anagnostopoulos C, Bhardwaj P, et al. Comparison of equilibrium radionuclide ventriculography with cardiovascular magnetic resonance for assessing the systemic right ventricle after Mustard or Senning procedures for complete transposition of the great arteries. *Am J Cardiol* 2003;**92**:640–3.
- 117 **Lissin LW**, Li W, Murphy DJ Jr, et al. Comparison of transthoracic echocardiography versus cardiovascular magnetic resonance imaging for the assessment of ventricular function in adults after atrial switch procedures for complete transposition of the great arteries. *Am J Cardiol* 2004;**93**:654–7.
- 118 **Dos I**, Teruel L, Ferreira U, et al. Late outcome of Senning and Mustard procedures for correction of transposition of the great arteries. *Heart* 2005;**91**:652–6.
- 119 **Cui W**, Anno H, Kondo T, et al. Right ventricular volume measurement with single-plane Simpson's method based on a new half-circle model. *Int J Cardiol* 2004;**94**:289–92.
- 120 **Allwork SP**, Bentall HH, Becker AE, et al. Congenitally corrected transposition of the great arteries: morphologic study of 32 cases. *Am J Cardiol* 1976;**38**:910–23.
- 121 **Valdes-Cruz LM**, Cayre RO. Congenitally corrected transposition of the great arteries. In: Valdes-Cruz LM, Cayre RO, eds. *Echocardiographic diagnosis of congenital heart disease. An embryologic and anatomic approach*. Philadelphia: Lippincott-Raven, 1999:277–88.
- 122 **Caso P**, Ascione L, Lange A, et al. Diagnostic value of transesophageal echocardiography in the assessment of congenitally corrected transposition of the great arteries in adult patients. *Am Heart J* 1998;**135**:43–50.
- 123 **Daliento L**, Corrado D, Buja G, et al. Rhythm and conduction disturbances in isolated, congenitally corrected transposition of the great arteries. *Am J Cardiol* 1986;**58**:314–8.
- 124 **Lundstrom U**, Bull C, Wyse RK, et al. The natural and “unnatural” history of congenitally corrected transposition. *Am J Cardiol* 1990;**65**:1222–9.
- 125 **Graham TP Jr**, Parrish MD, Boucek RJ Jr, et al. Assessment of ventricular size and function in congenitally corrected transposition of the great arteries. *Am J Cardiol* 1983;**51**:244–51.
- 126 **Benson LN**, Burns R, Schwaiger M, et al. Radionuclide angiographic evaluation of ventricular function in isolated congenitally corrected transposition of the great arteries. *Am J Cardiol* 1986;**58**:319–24.
- 127 **Dimas AP**, Moodie DS, Sterba R, et al. Long-term function of the morphologic right ventricle in adult patients with corrected transposition of the great arteries. *Am Heart J* 1989;**118**:526–30.
- 128 **Graham TP Jr**, Bernard YD, Mellen BG, et al. Long-term outcome in congenitally corrected transposition of the great arteries: a multi-institutional study. *J Am Coll Cardiol* 2000;**36**:255–61.
- 129 **Rutledge JM**, Nihill MR, Fraser CD, et al. Outcome of 121 patients with congenitally corrected transposition of the great arteries. *Pediatr Cardiol* 2002;**23**:137–45.
- 130 **Prieto LR**, Hordof AJ, Secic M, et al. Progressive tricuspid valve disease in patients with congenitally corrected transposition of the great arteries. *Circulation* 1998;**98**:997–1005.
- 131 **Rapaport E**. Natural history of aortic and mitral valve disease. *Am J Cardiol* 1975;**35**:221–7.
- 132 **Bonow RO**, Carabello B, de Leon AC, et al. ACC/AHA guidelines for the management of patients with valvular heart disease. Executive summary. A report of the American College of Cardiology/American Heart Association task force on practice guidelines (committee on management of patients with valvular heart disease). *J Heart Valve Dis* 1998;**7**:672–707.
- 133 **Fogel MA**, Weinberg PM, Fellows KE, et al. A study in ventricular-ventricular interaction. Single right ventricles compared with systemic right ventricles in a dual-chamber circulation. *Circulation* 1995;**92**:219–30.
- 134 **Hornung TS**, Bernard EJ, Jaeggi ET, et al. Myocardial perfusion defects and associated systemic ventricular dysfunction in congenitally corrected transposition of the great arteries. *Heart* 1998;**80**:322–6.
- 135 **Hornung TS**, Bernard EJ, Celermajer DS, et al. Right ventricular dysfunction in congenitally corrected transposition of the great arteries. *Am J Cardiol* 1999;**84**:1116–9, A10.
- 136 **Hauser M**, Bengel FM, Hager A, et al. Impaired myocardial blood flow and coronary flow reserve of the anatomical right systemic ventricle in patients with congenitally corrected transposition of the great arteries. *Heart* 2003;**89**:1231–5.
- 137 **van Son JA**, Danielson GK, Huhta JC, et al. Late results of systemic atrioventricular valve replacement in corrected transposition. *J Thorac Cardiovasc Surg* 1995;**109**:642–52, discussion 652–3.
- 138 **de Roos A**, Roest AA. Evaluation of congenital heart disease by magnetic resonance imaging. *Eur Radiol* 2000;**10**:2–6.
- 139 **Sahn DJ**, Vick GW. Review of new techniques in echocardiography and magnetic resonance imaging as applied to patients with congenital heart disease. *Heart* 2001;**86**(suppl II):ii41–53.
- 140 **Taylor AM**, Thorne SA, Rubens MB, et al. Coronary artery imaging in grown up congenital heart disease: complementary role of magnetic resonance and x-ray coronary angiography. *Circulation* 2000;**101**:1670–8.