Cardiovascular magnetic resonance in adults with previous cardiovascular surgery

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Cardiovascular magnetic resonance (CMR) is a versatile non-invasive imaging modality that serves a broad spectrum of indications in clinical cardiology and has proven evidence. Most of the numerous applications are appropriate in patients with previous cardiovascular surgery in the same manner as in non-surgical subjects. However, some specifics have to be considered. This review article is intended to provide information about the application of CMR in adults with previous cardiovascular surgery. In particular, the two main scenarios, i.e. following coronary artery bypass surgery and following heart valve surgery, are highlighted. Furthermore, several pictorial descriptions of other potential indications for CMR after cardiovascular surgery are given.

Keywords magnetic resonance • cardiovascular surgery • coronary bypass • valve replacement • aorta

Introduction

Cardiovascular surgery is used in a wide variety of indications to treat cardiovascular diseases in adults. Thorough follow-up is mandatory to optimally guide these patients and appropriately discover potential complications. It is predominantly performed by clinical interrogation and transthoracic echocardiography (TTE), sometimes accompanied by exercise test, and if necessary extended by computed tomography, cardiovascular magnetic resonance (CMR), or invasive measures.

CMR acquires images of the heart and the large vessels non-invasively and without ionizing radiation. Specific image contrasts and characteristics can be selected depending on the clinical question, often enhanced by intravenous administration of gadolinium-based contrast agents. Images can be acquired as a dynamic series or as a still image in any desired plane independent from the patient’s physique. CMR provides information about cardiac dimensions and function [e.g. steady-state free-precession (SSFP) cine imaging], myocardial perfusion (first pass of contrast), oedema (T2-weighted imaging), necrosis or fibrosis (late gadolinium enhancement), blood flow (phase-contrast imaging), as well as vessel geometry and morphology (e.g. contrast-enhanced angiography).1 Hence, a comprehensive assessment of both anatomy (e.g. myocardial scar in coronary artery disease or orifice area in valvular heart disease) and function (e.g. myocardial perfusion or regurgitant volume, respectively) is possible.

Compared with TTE, which is the first-line imaging modality, CMR has the main advantage of unimpaired image quality independent from post-surgical adhesions, obesity, or pulmonary emphysema, which allows an accurate assessment of cardiovascular function and morphology (Table 1).

The potential of CMR in adults with previous cardiovascular surgery is potentially under-represented in the current guidelines.2,3 This review is intended to give a summary regarding CMR after coronary artery bypass grafting (CABG) and after valvular surgery, and to provide a pictorial overview of various less-frequent indications for CMR in adults with previous cardiovascular surgery.

Safety of CMR after cardiovascular surgery

General contraindications and safety measures for CMR have to be regarded in patients with previous cardiovascular surgery in the same way as in every other patient. Additional aspects regarding implants have to be considered.4 The sternal wires do not raise safety concerns during CMR, and usually image interpretation is not impeded unless the region of interest is very close to the artefacts caused by the sternal wires.5 Vascular clips used to ligate side branches of a venous graft for coronary bypass, do in general not present an additional risk. The majority of mechanical and stented
heart valve prostheses as well as annuloplasty rings displayed measurable, yet relatively minor magnetic field interactions at both 1.5 and 3 T. Compared with the force exerted by the beating heart, the actual attractive forces by the magnetic field were minimal. Most new prostheses for transcatheter aortic valve implantation (TAVI) are labelled as MR-conditional. Many patients with prior cardiovascular surgery carry an implantable electronic device like pacemakers or implantable cardioverter defibrillators (ICDs), which was considered a contraindication to MR imaging. Possible interactions are movement of the pulse generator or leads, modification of the function, inappropriate sensing, triggering, or activation, excessive heating and induced currents in the leads, and electromagnetic interference. Recent data suggest that certain pacemaker and ICD systems may be MR safe under certain conditions. Thus, on a case-by-case basis, where the diagnostic benefit from MR imaging may outweigh the risks, MR may be considered in pacemaker and ICD patients. Advances in cardiac device technology have recently led to the first generation of MR-conditional devices. Generally, it is recommended to check the manufacturers’ information before performing a CMR study in subjects with implants.

CMR after coronary artery bypass grafting

Stress perfusion CMR after CABG

Stress perfusion CMR analyses the first pass of an extracellular contrast agent bolus within the myocardium during intravenous administration of a vasodilator that causes hyperaemia. The hyperaemic flow is compromised in myocardial segments that are supplied by a significantly stenosed vessel because of the drop of coronary perfusion pressure downstream of the stenosis. Segments with a perfusion defect in relation with the hyperaemic myocardium will be identifiable by a lower signal intensity (Figure 1).

There is fundamental evidence that stress perfusion CMR detects native coronary artery stenosis with high diagnostic accuracy, comprising a sensitivity and specificity around 91 and 81%, respectively. However, there have been concerns whether this method is also appropriate to assess myocardial perfusion in patients after CABG, who were often under-represented in previous stress perfusion trials. There might be altered myocardial contrast kinetics owing to more complex myocardial perfusion and different distances of the contrast bolus through different bypasses and native coronary vessels, thereby possibly imitating a perfusion defect.

Kelle et al. applied semi-quantitative perfusion parameters in patients with CABG to assess possible differences in epicardial contrast kinetics in areas supplied by native coronary arteries without significant stenosis and by CABG without significant stenosis. They observed a short delay regarding the time to 50 and 100% maximal signal intensity between areas perfused by coronary arteries with bypasses compared with native coronary arteries without bypasses. Nevertheless, they concluded that since the delay was only short and since there was similar peak enhancement once the contrast was in the myocardium, the possibly differing contrast kinetics through grafts and native vessels did not limit the accuracy of stress perfusion in patients post-CABG. Arnold et al. quantified absolute myocardial blood flow by stress perfusion CMR in patients with CABG. They did not observe a systematically underestimated blood flow in graft-subtended territories and also concluded that this methodology to evaluate myocardial perfusion in patients with CABG was justified.

Regarding the diagnostic accuracy of stress perfusion CMR in patients with CABG, a multi-centre study reported a sensitivity of 79% and a specificity of 77% to detect a coronary artery stenosis of ≥70%. Thereby, the sensitivity and specificity were reduced compared with patients with suspected coronary artery disease in the same study (94 and 87%). Klein et al. reported a sensitivity of 70% and a specificity of 90% to detect a coronary artery stenosis of >50% in patients with prior CABG.

Hence, even though experimental studies indicated that there should be no relevant differences in contrast media kinetics between patients with CABG and those without, two clinical studies revealed a decrease in overall diagnostic accuracy in patients with CABG compared with those without. Apart from the mentioned differences in the contrast transit time through native vs. bypass vessels, the presence of significant collateral flow in patients with CABG, who mostly have multi-vessel disease, may have impact on the diagnostic accuracy of stress perfusion CMR. Under consideration of that limitation, stress perfusion CMR can be used appropriately in patients with CABG.

Dobutamine wall motion CMR after CABG

Dobutamine stress CMR is a valid alternative to stress perfusion CMR, in particular in patients with impaired renal function as no contrast agent is required. Left ventricular function is assessed using cine imaging at rest, and subsequently during increasing dosages of intravenously administered dobutamine until an age-predicted heart rate response is obtained. In the presence of a relevant coronary stenosis,
the stress promotes an oxygen supply/demand mismatch that leads to left ventricular wall motion abnormalities.9 A meta-analysis reported a sensitivity and specificity of 83 and 86%, respectively, to detect a coronary artery stenosis of >50%.10 There should be no difference in the diagnostic accuracy between patients with CABG and those without, even though explicit comparative data are missing. It might be speculated that patients after cardiovascular surgery indeed benefit from the use of dobutamine CMR instead of dobutamine echocardiography. This assumption is based on studies that demonstrated a significant diagnostic advantage of dobutamine CMR in patients with impaired echo image quality, which is quite common in post-surgical subjects.15

MR coronary angiography after CABG

In symptomatic patients with CABG, the visualization of the bypass grafts is sometimes desired to assess graft stenosis or occlusion. High-resolution CMR achieved a good diagnostic performance to detect graft occlusion and stenosis of ≥70%.16 However, even though MR coronary angiography has improved since then, it is still restricted to centres with specific expertise and still inferior compared with computed tomography. Therefore, MR coronary angiography to assess CABG has been evaluated as ‘inappropriate’ in recent appropriateness criteria.2

CMR for prognostic assessment after CABG

Several studies have demonstrated that CMR stress tests provide information about the risk for future cardiovascular events. In patients with known or suspected coronary artery disease with normal CMR stress test, the 3-year event-free survival was 99.2%.17 In most of these studies, patients with prior CABG made up a minority.17,18 Theoretically, the association of normal or abnormal stress test with future cardiovascular events should persist in patients after CABG. However, the inferior diagnostic accuracy of stress perfusion CMR after CABG has to be kept in mind and probably, influences the prognostic power, even though specific data for a CABG sample are not available.

Type 5 myocardial infarction is related to CABG and is defined by a specific postoperative elevation of cardiac biomarker values, imaging evidence of new loss of viable myocardium or new regional wall motion abnormality.19 Imaging of new loss of viable myocardium is achievable by CMR with high sensitivity using the late enhancement technique.20 Lim et al.21 found new late enhancement in 9 from 28 patients undergoing CABG. In a study by Kwong et al., which analysed the impact of late enhancement on prognosis in patients without known myocardial infarction, 25 of 195 (13%) exhibited unknown late enhancement, whereas the overall prevalence of late enhancement in the whole study group was only 23%. It is known that even very small amounts of late enhancement were associated with the occurrence of major adverse cardiac events.22 This observation is confirmed by Rahimi et al., who reported that the presence of late enhancement after CABG yielded a three-fold increase of adverse events during 3-year follow-up.23 These data underline that periprocedural myocardial infarction is common after CABG, and that CMR can be helpful to confirm this diagnosis.

CMR after heart valve surgery

All patients after heart valve surgery require careful follow-up.1 However, CMR currently plays a minor role, even though actual appropriateness criteria rank the characterization of prosthetic cardiac valves as highly appropriate in patients with technically limited images from TTE or transoesophageal echocardiography (TEE).2 Additionally, many of the CMR techniques and cut-planes that are established to assess native heart valves can be applied for valve prostheses.24
CMR to assess bioprosthetic heart valves

Biological prostheses include homografts, pulmonary autografts, and xenografts (stentless and stented) made of porcine heart valves or bovine pericardium. The haemodynamic performance of prosthetic heart valves is mainly determined by (i) transprosthetic blood flow velocity, (ii) orifice area, and (iii) trans- or paravalvular regurgitation.25

CMR to assess peak transprosthetic velocity of bioprostheses

Phase-contrast CMR can principally assess transprosthetic blood flow velocities. However, several caveats have to be considered: (i) it is difficult to assess on which level the peak velocity appears and hence which cut-plane has to be chosen. (ii) The limited temporal resolution of phase-contrast studies leads to an underestimation of the peak velocity. (iii) As the velocity is averaged over the slice thickness, the peak velocity is underestimated. (iv) There is an increasing discrepancy between CMR and Doppler echo with an increasing peak velocity, which is attributed for instance to an enhanced turbulent flow.26 (v) The valvular plane exhibits a significant excursion during each cardiac cycle, whereas the cut-plane is usually static. For all these reasons, the quantification of transprosthetic blood flow velocity is, in general, not recommended.

CMR to assess the orifice area of bioprostheses

The orifice area of bioprostheses can generally be quantified by CMR cine imaging very accurately. For this purpose, steady-state free-precession (SSFP) cine imaging is preferred, as it allows for the accurate measurement of the orifice area.5,28
free-precession cine images are acquired perpendicular to the transprosthetic jet covering the whole prosthesis. The cut-plane with the smallest orifice area is selected and in this one, the temporal phase with the largest orifice area is chosen in accordance to the approach in aortic stenosis. Finally, the orifice area is delineated by manual planimetry. A comparison of CMR with TTE (continuity equation) and TEE (direct planimetry) in patients with biological aortic valve replacement revealed close agreement of the orifice area between CMR, TTE, and TEE with acceptable observer dependency. The same principle has been applied to patients with mitral bioprostheses (Figure 2). Despite the more extensive excursion of the mitral compared with the aortic annulus and the high prevalence of arrhythmia, the comparative analysis of the orifice area between CMR (direct planimetry) and TTE (pressure half-time derived) demonstrated a

Figure 3  Pulmonary valve replacement imaged by CMR SSFP cine imaging. (A and C) Long axis in diastole and systole. (B + D) Short axis in diastole and systole. The white arrows point to the pulmonary valve prosthesis.

Figure 4  Artefacts caused by the stent material of bioprosthetic heart valves in the aortic position. Top: Medtronic Corevalve® #29 in a three-chamber (left) and short-axis view in diastole (right). Bottom: Edwards Perimount® #23 in a short-axis view in systole (left) and diastole (right).
close agreement. The same approach can be applied to the pulmonary and tricuspid position (Figure 3). The majority of stented bioprostheses caused only minimal susceptibility artefacts. However, few prosthetic stents containing a cobalt–chromium spring alloy, as well as the CoreValve® prosthesis, which is composed from a porcine-pericardial valve mounted into a self-expanding nitrinol stent ranging from the left ventricular outflow tract beyond the sino-tubular junction, led to extensive artefacts, which make the delineation of the orifice area infeasible (Figure 4).

The decision whether a bioprosthesis has a normal or an abnormal orifice area is mostly based on the comparison of the individual result with published reference values. In default of specific CMR data, reference values obtained by echocardiography have to be used at that time. Experiments in a pulsatile flow phantom demonstrated that orifice areas of different bioprostheses agreed close between CMR and echocardiography.

The assessment of the orifice area of bioprostheses is crucial to determine the presence of patient-prosthesis mismatch (PPM). PPM is present if the prosthesis itself works adequately, but its orifice area is too small in relation to the haemodynamic demand of the individual patient. The evidence is growing that PPM is associated with increased postoperative morbidity and mortality, even though there is still a controversial debate. We speculate that one reason for contradicting results of previous studies in the field of PPM is the challenge to accurately estimate the orifice area by TTE—in particular, in patients with prior sternotomy. We think that the use of CMR in studies about PPM may improve the accuracy of the determination of PPM and may lead to more consistent data (Figure 5).

Bioprostheses exhibit structural valve deterioration over time, which may cause prosthetic stenosis. In addition to the direct depiction of the incomplete opening of one or more prosthetic cusps by SSFP cine imaging, CMR imaging can sometimes visualize the underlying cause (e.g. pannus ingrowth or thrombosis). As CMR is strong in assessing soft tissue, whereas computed tomography is very sensitive to calcified tissue, a comprehensive multimodality approach can be helpful in selected cases to determine the origin of prosthetic dysfunction and to guide therapy (Figure 5).

CMR to assess regurgitation of bioprostheses

Regurgitation of heart valve prosthesis can occur in two ways: (i) transvalvular backflow, if the closing mechanism of the prosthesis is imperfect (e.g. as a consequence of structural valve deterioration), or (ii) paravalvular backflow, if there is leakage between the prosthetic sewing ring and the surrounding tissue. Even though the main jet may sometimes be visible in CMR cine images, the absence of any jet does not preclude prosthetic regurgitation, as jet visualization depends on many cofactors (e.g. echo time, slice orientation). Furthermore, it is rarely feasible to differentiate between trans- or paravalvular regurgitation using CMR. Instead, the strength of CMR is to quantify blood flow volumes in order to determine the presence and the severity of any regurgitation. For prostheses in the aortic position, the antegrade and retrograde blood flow in the ascending aorta are quantified by phase-contrast acquisitions to calculate the regurgitant fraction—similarly to the approach in native aortic regurgitation (Figure 6). Care should be taken to keep adequate distance to the prosthesis, as phase-contrast acquisitions may be prone to magnetic field inhomogeneities. When interpreting the regurgitant fraction, it has to be considered that the thresholds for mild, moderate, and severe

Figure 5 Complications of aortic bioprostheses depicted by CMR SSFP cine imaging. (A–D) Moderate PPM in a woman with a #21 Mitroflow® prosthesis that postoperatively exhibited an orifice area of 1.2 cm² (index 0.75 cm²/m²) and a peak transprosthetic pressure gradient of 51 mmHg during TTE. (E–H) Structural valve degeneration in a patient with bioprosthetic aortic valve (Shelhigh® #31). (E + G) show the impaired systolic opening in a three-chamber and short-axis view. (F + H) show the computed tomography with extensive calcification of the non-coronary cusp.
valvular regurgitation seem to differ between CMR on the one hand and echo or catheter on the other. Based on the AHA/ACC guidelines for valvular heart disease, the regurgitant fraction cut-off for severe aortic regurgitation is 50%, whereas based on CMR measurements it seems to be around 30%.

The similar approach as outlined for aortic prostheses can be applied to assess pulmonary prostheses by measuring the antegrade and retrograde blood flow in the main pulmonary artery (similar to native pulmonary regurgitation). For prostheses in mitral and tricuspid position, the approach differs and is less robust: the stroke volume of the left (right) ventricle is calculated by a left (right) ventricular volumetry in SSFP cine images and by a phase-contrast blood flow measurement in the ascending aorta (pulmonary artery). The difference between both volumes in theory corresponds to the regurgitant volume of the atrioventricular valve. This technique is prone to measurement errors as it is a composition of two measurements with two different MR acquisition techniques.

As stated above, the visualization of regurgitant jets is limited with CMR. Echocardiography is clearly superior regarding the paravalvular and transvalvular aspect, even in the presence of multiple jets. However, the quantification of their haemodynamic load is often a challenge. CMR appears to be a valuable complementary tool as it quantifies the total haemodynamic load that is caused by valvular regurgitation independent from the number of jets. Multiple paravalvular jets recently received increasing attention with the advent of TAVI, where moderate or severe paravalvular leakage were associated with increased late mortality. A recent study comparing TTE, CMR, and invasive angiography to assess prosthetic regurgitation after TAVI reported a close agreement between CMR and angiography, whereas TTE disagreed significantly from both.

CMR to assess prosthetic endocarditis or thrombosis
Prosthetic endocarditis or thrombosis are usually—apart from extensive findings—not evaluable by CMR due to constraints of spatial resolution and the non-real-time image acquisition over several cardiac cycles, which may miss structures with asynchronous mobility. Furthermore, stent-induced artefacts hinder the assessment of the surrounding tissue regarding abnormalities (e.g. abscess). TEE remains the standard imaging modality in this clinical question.

CMR to assess mechanical heart valves
The assessment of the peak blood flow velocity is not recommended for mechanical prostheses. In addition to the arguments mentioned for bioprosthetic devices, the distribution of the
blood jet by the split orifice area of mechanical prostheses into several jets further limits every attempt to quantify peak flow. The orifice area of mechanical prostheses cannot be quantified by CMR due to significant susceptibility artefacts caused by the prosthetic material (Figure 7). Only the type of prosthesis (e.g. bileaflet or tilting disc) is sometimes noticeable, and a rough assessment of the opening mechanism can in some cases be estimated. Prosthetic regurgitation of mechanical prostheses can be assessed in a similar fashion as explained for bioprostheses. CMR is not recommended to analyse prosthetic endocarditis or thrombosis (see description for bioprostheses).

CMR to assess pulmonary autografts (Ross)
The Ross procedure describes the transposition of the pulmonary valve into the aortic position to treat aortic valve disease, while a homograft is implanted in the pulmonary position. Both substituted valves require a careful follow-up. In addition, the adjacent vessels (ascending aorta and pulmonary artery) tend to dilate and may cause valvular regurgitation, which actually constitutes one of the main indications for reoperation in these patients. CMR provides a comprehensive assessment in this situation: (i) valvular orifice and regurgitation can be assessed as outlined before. (ii) Thoracic aorta and main pulmonary arteries can be visualized by three-dimensional (3D) techniques allowing multiplanar reformation. (iii) The ventricular volumes and mass can be assessed to monitor disease relevance in the presence of valvular regurgitation. This is of special importance for the interplay between the pulmonary regurgitation and the right ventricle, as the evaluation of both can be very challenging by echocardiography. (iv) As the coronaries are re-implanted in the neo-aorta, the question of post-surgical myocardial ischaemia or regional wall motion abnormality may arise. Stress perfusion CMR and late enhancement imaging may be considered (Figure 8).

CMR after heart valve repair
Mitral valve repair is the preferred method to treat mitral valve regurgitation, if technically suitable, compared with mitral valve replacement due to less postoperative complications. A stenotic mitral valve can be reconstructed by commissurotomy if the commissures are fused in the absence of high-grade calcification of the leaflets. As stated above for mitral prostheses, the assessment of post-repair regurgitation by CMR is limited, whereas the visualization and quantification of the mitral orifice area is feasible by SSFP cine imaging. Isolated aortic valve repair is performed rarely. The severity of postoperative aortic regurgitation is an important indicator of surgical success. Similar to in native aortic valves, CMR allows the direct visualization of the anatomy of the aortic root and the quantification of the regurgitant fraction (Figure 9).

CMR to assess the ascending aorta after heart valve surgery
Ascending aortic dilation after aortic valve replacement is encountered frequently. The underlying pathology may be a structurally abnormal aortic wall itself or the haemodynamic load.

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Figure 7  Mechanical heart valve prosthesis depicted by SSFP cine imaging. (A–D) Mechanical heart valve prosthesis (St Jude Medical #29) in the aortic position in diastole (A and B) and systole (C and D). The arrow points to the prosthesis. In (D), the opening of the bileaflet valve can roughly be assessed. (E + F) Mechanical heart valve prosthesis (Medtronic #29) in the mitral position. A regurgitant jet is noticed on the three-chamber view in systole (E; white arrow), whereas the prosthetic orifice cannot be evaluated due to a prosthetic-related artefact and impaired image quality due to atrial fibrillation (F; white arrow).
detects aortic dilation after aortic valve replacement far more frequent than TTE, as TTE only depicts the very proximal ascending aorta, whereas dilatation often occurs more distally. As non-contrast-enhanced CMR angiography techniques have been improved, they can be used for repeated follow-up studies instead of accumulating contrast media application.

CMR for cardiac chamber quantification after heart valve surgery

The assessment of cardiac dimensions and function is part of the standard follow-up of patients after heart valve surgery. For instance, the regression of left ventricular hypertrophy is regarded as an important target of aortic valve replacement, and the follow-up of right ventricular function is very important after surgery on the pulmonary valve, in particular in adults with congenital heart disease. CMR has generally evolved as the gold standard to assess cardiac dimensions and function of both the left and right ventricle. It allows direct quantification of cardiac volumes in a 3-D approach, instead of calculating dimensions based on geometric assumption—which are a challenge to define especially for the right ventricle. In particular in post-surgical subjects, CMR is valuable to overcome frequently encountered impaired echocardiographic windows.

CMR after other cardiovascular surgical interventions

CMR after ascending aortic surgery

Surgery of the ascending aorta is mainly done in ascending aortic aneurysms and dissections. During follow-up, CT or CMR are
recommended if TTE remained inconclusive or if the distal part of the ascending aorta was involved. Compared with CT, CMR has the advantage of the lack of ionizing radiation, no obligatory need for contrast media, and the combination of functional and morphologic information\textsuperscript{45} (Figure 10).

If aortic regurgitation is mainly caused by the dilation of the aortic root, aortic valve sparing operations are used as treatment.\textsuperscript{46} Postoperative assessment of the severity of any residual valvular regurgitation and follow-up evaluation of ascending aortic anatomy are important. Both aspects can be delivered by CMR in an accurate and robust fashion. In addition, the use of novel imaging methods like 4D flow may be helpful to analyse the blood flow dynamics in the ascending aorta in order to identify the best surgical approach.\textsuperscript{47}

**CMR after ventricular reconstruction**

The value of surgical ventricular reconstruction [e.g. septal anterior ventricular exclusion (SAVE) or Dor], during which tissue is removed from the left ventricular wall with the aim of restoring a more physiological left ventricular volume and shape, is still uncertain, but may be chosen in selected patients.\textsuperscript{48} The post-surgical state and the implanted patch material sometimes complicate the echocardiographic interrogation. The combination of functional information by

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**Figure 9** CMR after aortic valve reconstruction. (A + D + E) show the preoperative state of a bicuspid aortic valve with severe regurgitation. (B + F + G) show the result after surgical reconstruction of the aortic valve. The competent closure during diastole (G vs. E) is noticeable. (C + H) Phase-contrast flow measurement before surgery revealed a regurgitant fraction of 50\% (C) that decreased postoperatively to 17\% (H).

**Figure 10** Persistent Cabrol shunt. Images of a patient with increasing dyspnoea 4 years after surgery for an aortic Type A dissection including a Cabrol shunt. The right chambers were enlarged and dysfunctional (left; asterisk). There was a perfused false lumen between the aortic graft and the native aortic wall (left; white arrow), and the Cabrol graft originated from the false lumen (middle, white arrow) with course into the right atrium (right; white arrow). The blood-typical signal intensity within the graft confirmed patency and explained the patient’s severe right heart failure to the persistent iatrogenic left-to-right shunt.\textsuperscript{45}
cine imaging that provides the pattern of wall motion as well as accurate cardiac volumes, together with morphologic data about the distribution of scar by late enhancement imaging, makes CMR a valuable tool during preparation and follow-up. However, the implanted patch material may lead to signal loss (Figure 11).

**Figure 11** CMR after left ventricular restoration. Top: (A) SSFP cine imaging detected a larger aneurysm of the lateral wall (white arrow). (B) Late enhancement imaging identified a large thrombus within the aneurysm (asterisk). (C) Postoperatively, the left ventricle appeared appropriately reshaped in SSFP cine images (white arrow). Middle: (A) After left ventricular restoration, a leakage (asterisk) between the neo-apex (white arrow) and the original apex occurred. (E) Perfusion imaging confirmed the blood flow in the cavity (asterisk). (F) Late enhancement images show the extensive scarring of the left ventricular apex (white arrow). Bottom: (G) Late enhancement depicts extensive scarring of the left ventricular apex (white arrows). (H) After surgical restoration, the reshaped left ventricle (black arrow) is assessable on SSFP cine images. (I) Late enhancement imaging gave suspicion of a thrombus next to the patch material (asterisk).

**CMR after surgery in hypertrophic cardiomyopathy**

Transaortic septal myectomy is currently considered the most appropriate treatment for the majority of patients with obstructive hypertrophic cardiomyopathy (HCM) and severe symptoms unresponsive to medical therapy. It has been shown that the degree of obstruction of the left ventricular outflow tract can be assessed by CMR by using cine imaging with direct planimetry, which is also suitable to assess the effect of septal myectomy and to monitor the patients. In addition, CMR provides useful information about the ventricular shape and function and the myocardial texture in HCM patients.

**CMR after surgery of cardiac masses**

CMR has a significant value to detect and to differentiate cardiac masses. In particular, the discrimination towards thrombotic material is important, but also the determination of the type of tumour is often feasible by using a combination of various CMR techniques. After surgery, CMR may be useful to evaluate the surgical result, to detect surgical sequelae, or to find early stages of any recurrence.

**CMR in adults after surgery for congenital heart disease**

Advances in paediatric cardiology and cardiac surgery have enabled the survival into adulthood of most patients born with congenital cardiovascular malformations. The operations performed for more complex malformations require a lifelong follow-up. Thereby, the versatility and comprehensiveness of CMR offers numerous investigative possibilities. The European Society for Cardiology has summarized them in a recent recommendation paper.
CMR to assess the pericardium after cardiovascular surgery

CMR is regarded as highly appropriate to evaluate pericardial conditions. The most frequent abnormality after cardiovascular surgery is pericardial effusion. If the acoustic window is restricted or if the effusion confined to a hidden compartment, CMR may be helpful. The diagnosis of constrictive pericarditis is problematic, and management consequences are profound. CMR offers a valuable multiparametric approach. Cine images with tagging gridscan reveal myo-pericardial adhesion, real-time cine images of the right and left ventricle demonstrate the septal bounce during inspiration, and late enhancement images show the thickening and contrast uptake of the diseased pericardium (Figure 12).

Conclusions

In adults with prior cardiovascular surgery, CMR adds important information in many clinical and scientific scenarios. In particular, the two main surgical interventions, CABG and heart valve replacement, offer a lot of indications that justify the use of comprehensive CMR imaging.

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Figure 12  Pericardial complications after cardiovascular surgery assessed by CMR. (A) Severe pericarditis after Ross surgery with a complex organized pericardial effusion. (B + C) Extensive pericardial effusion after aortic valve replacement surrounding the left heart (asterisk). The transverse thoracic survey (C) clearly delineates the pericardial effusion (asterisk) from the pleural effusion (black arrow). (D – F) Patient with right-sided heart failure after aortic valve replacement. (D + F) Real-time images showed septal bowing towards the left ventricular cavity on inspiration consistent with ventricular interdependence, a hallmark of pericardial constriction. (G) CMR demonstrated thickening and late gadolinium enhancement of the pericardium. (G) Tagged-cine imaging showed intact pericardial/epicardial gridlines during systole consistent with concordant motion of the two.

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**Giant pulmonary mass complicating pulmonary homograft replacement**

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A 40-year-old male with a history of i.v. drug abuse was referred to our hospital because of dyspnoea. He had a history of pulmonary valve endocarditis in 2001 and pulmonary homograft was implanted 2 years later because prosthetic endocarditis. The patient complained of dyspnoea on moderate exertion (New York Heart Association functional class II/IV) and the physical examination revealed a systo-diastolic murmur best heard at the left upper sternal border with two distinct components: high-frequency holosystolic and low-frequency protodiastolic murmur. Chest radiography showed a rounded well-defined mass in the left lung that communicates with aortopulmonary window (Panel A). Transthoracic echocardiography showed a dilated right ventricle with severely depressed systolic function as well as pulmonary homograft dysfunction with severe stenosis (maximum gradient 64 mmHg) and insufficiency. Transoesophageal echocardiography confirmed these findings and also showed marked dilation of the main pulmonary artery (Panel B). Moreover, cardiac magnetic resonance was performed showing the presence of a large pseudoaneurysm (78 × 73 mm of diameter) communicating with the main pulmonary artery distal to the valvular plane (Panels C and D). Supplementary data online, Videos S1 and S2). The patient underwent surgery and a new pulmonary homograft was implanted, excluding the aneurysm sac. He remained asymptomatic at 2-month follow-up.

Pseudoaneurysm of the main pulmonary artery is a rare complication after homograft placement. The clinical presentation ranges from asymptomatic patients with a new pulmonary mass to dyspnoea, chest pain, and life-threatening haemorrhage. The approach is mostly surgical and resection of the mass should be conducted to avoid serious complications.

Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.