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What's new in Magnetic Resonance Imaging?

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MAGNETIC RESONANCE IMAGING OF THE HEART has been possible for many years.[1] Only during the last few years have major improvements been in the quality of the images produced and, in particular, the speed of their acquisition. In terms of technology, the generation of commercially available clinical magnetic imaging systems that are currently being installed represent a major step forward. Improvements in the hardware of the magnetic resonance system, together with more much greater computing power, have now made practical high quality cardiac imaging an everyday reality. The value of non-invasive, high-resolution, cross-sectional images of the heart for the diagnosis and follow-up of structural heart disease has long been recognised. Practical problems, such as long imaging times, and artefact due to the movement of the patient, have stood in the way of its being used in many patients with congenital cardiac defects. Perhaps we should add to this the logistical problems of access to the magnetic resonance imaging service. In many centres, there is great competition for access to a limited resource. Because of this, cardiologists, who may have exclusive access to facilities for echocardiography and cardiac catheterisation, have tended to use tried and tested imaging rather than exploit the new technology. Wider availability of magnetic resonance systems, and the improvements in the technology, make this view no longer tenable. In some situations, for example imaging of the great arteries and veins, or measurement of ventricular volumes, magnetic resonance is established as the best imaging technique. In these situations, use of any other is undoubtedly second best. As I will explain in this review, magnetic resonance imaging can and will go much further.

Speed is the key. Recent improvements in protocols for imaging have had a dramatic effect on the time required to acquire images. Recognition of the importance of this probably explains the acronyms chosen to name the imaging sequence. Terms such as "FLASH", "SMASH", and "Turbo Spin Echo" abound.[2,3] Magnetic resonance can use a multitude of combinations of radiofrequency pulses and acquisitions to extract imaging information from the soft tissues of the body. Fine-tuning of these imaging protocols has led to improvements in speed and resolution so that now very rapid imaging is possible. A good quality service for magnetic resonance imaging depends upon close teamwork between the clinician and the medical physicists who manage the set-up of the system. It is not necessary for the cardiologist to understand the physics behind all these technical terms, but it is vital that they understand just what magnetic resonance can now achieve. The most important achievement of the recent developments is that imaging times have been reduced dramatically. This has led not only to shorter total scanning times, but has led to new and better ways of imaging.

Real-time imaging

Real-time magnetic resonance imaging has been possible for some years, but the resolution of real-time images has been poor. Now, high-resolution images can be provided of multiple slices through the heart acquired simultaneously at a rate of 30 frames per second or more.[4] This transforms magnetic resonance imaging from a static to a dynamic technique. Perhaps the best analogy is from a technique similar in concept to X-ray computed tomographic

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imaging to one more akin to a cross between echocardiography and X-ray fluoroscopy. This change has led to our view of the future of cardiac magnetic resonance changing radically. It now is possible to envisage it replacing X-ray fluoroscopy for the monitoring of invasive diagnostic and interventional procedures. This is highly likely to occur within a few years for procedures in the peripheral vasculature. Using it to monitor interventional procedures within the heart will present more technical challenges, but these are already beginning to appear surmountable.

For magnetic resonance to be used for the imaging and tracking of catheters and interventional devices within the circulation, they must be made of materials that are not affected by the very high magnetic field. Similarly, they must not cause artefacts or degradation of the image. Equally, they must be of a material that can be satisfactorily imaged.[5] Ferromagnetic materials cause too much distortion of the image and cannot be used. Other metals, such as titanium and some nickel alloys, can be imaged satisfactorily, and cause minimum distortion to the image. Plastic devices such as catheters can be coated in a paramagnetic compound to make them visible on the magnetic resonance image.

A novel way of tracking catheters and interventional devices is to build a miniature radiofrequency coil into the device. The coil will detect the signal produced by the imaging system. It can then transmit back its precise three-dimensional co-ordinates, which can be superimposed on the clinical images. By this technique, known as active tracking, the exact position of the device can be known at all times. This may open up new ways of positioning and controlling interventional devices.

Magnetic resonance imaging, nonetheless, does have a major drawback. It is a cross-sectional technique, unlike X-ray fluoroscopy, which produces a projectional rather than a cross-sectional image. Cross-sectional imaging is not ideal for tracking catheters and wires within the vasculature, and particularly within the heart. For the safe and accurate placement of many devices, it is necessary not just to image the tip of the device, but also the length of it, so that it can be monitored as it bends and coils within the great vessels and cardiac chambers. Experience with cross-sectional echocardiographic screening of interventional procedures has shown that it can successfully be used exclusively for straightforward technical procedures such as balloon atrial septostomy. It cannot, however, replace X-ray fluoroscopy for more complex procedures, where imaging the tip of the device is insufficient to manipulate it safely. To some extent, magnetic resonance imaging can produce an image similar to a projection image by acquiring a very large slice thickness. Doing this, however, will reduce resolution. It may be possible to extend a radiofrequency coil along the length of a catheter to overcome this, but this has yet to be proved effective. While this is a drawback, it seems likely that a combination of the use of paramagnetic materials, miniature radiofrequency coils, and thick slices or three-dimensional images, will make interventions guided exclusively by magnetic resonance within the heart a reality within the next decade. A combination of magnetic resonance imaging and X-ray fluoroscopy during a single procedure will probably be used within a much shorter timescale.

Three-dimensional magnetic resonance imaging

The second area in which faster times for imaging will make a big impact is with three-dimensional imaging. Magnetic resonance images are intrinsically three-dimensional, but are typically displayed as multiple slices. Multiplanar reformatting allows the data to be displayed in an imaging plane other than that in which it was originally acquired. The images, nonetheless, are still displayed as cross-sectional slices of the morphology. If multiple images are obtained during the cardiac cycle, then they can be displayed as a cine loop to show an apparently moving heart. Multiple imaging at different parts of the cardiac cycle is sometimes, somewhat confusingly, described as four-dimensional imaging.

There are broadly two ways of displaying images in three-dimensions. The first is maximum intensity projections. This is frequently used to display images from gadolinium enhanced contrast magnetic resonance angiograms. This imaging technique has been described in a previous article in this series.[6] It does not generate a true three-dimensional image, but represents a series of images of the vessels viewed from different angles (Fig. 1). Typically, the images are rotated around a vertical axis, but they can be rotated around a horizontal left-to-right, or anterior-posterior, axis. These images are best viewed as a cine loop, and the anatomy is not as easily appreciated from static images.

The widespread use of gadolinium contrast magnetic resonance angiography has achieved major improvements in imaging of the great arteries and veins. The decreased times required for acquisition means that the images can be obtained in less than thirty seconds. This makes acquisition feasible during a single held breath, so removing the respiratory artefact, one of the key problems in magnetic resonance imaging of the thoracic organs. With modern

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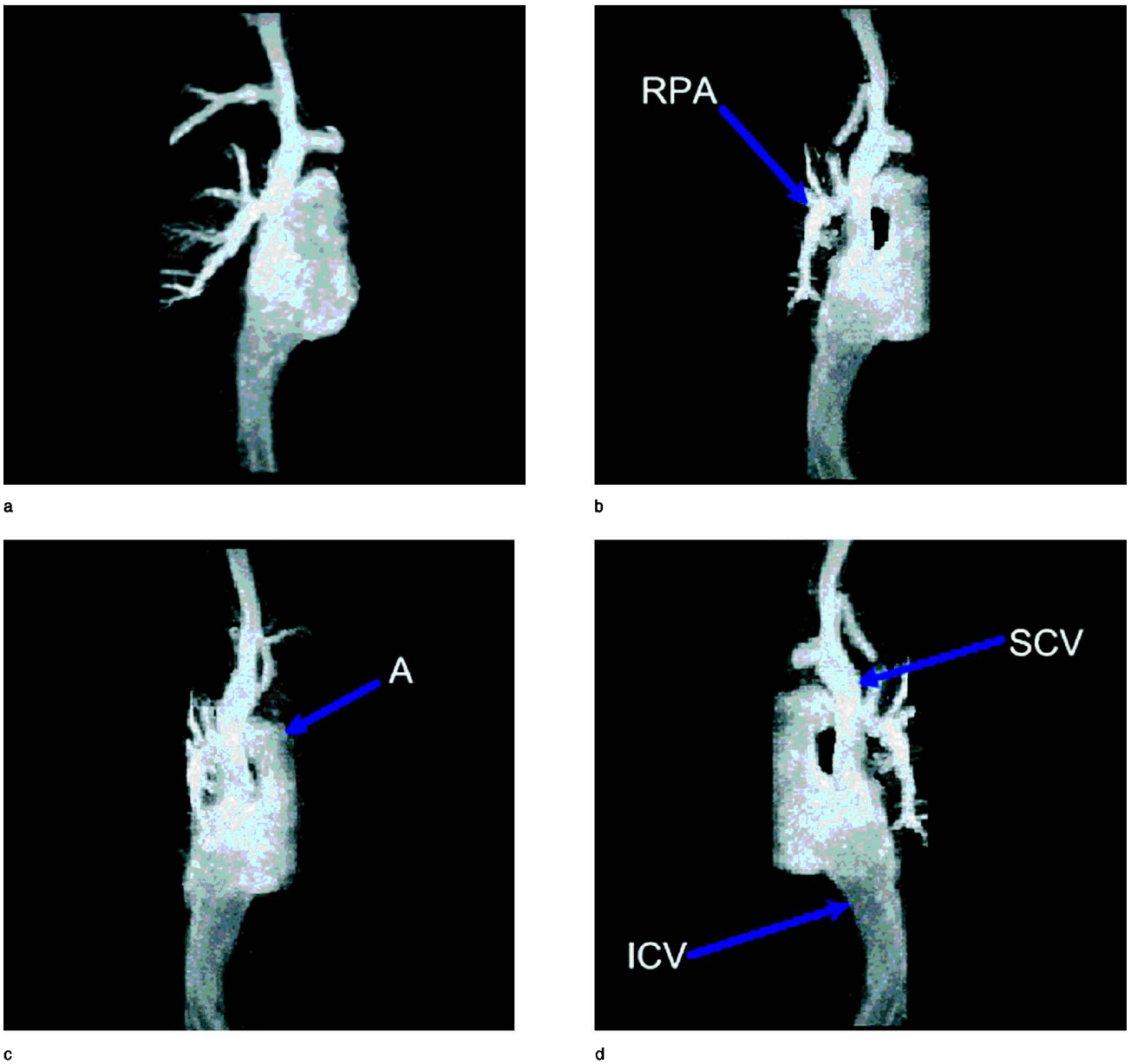


Figure 1.
These are four images from a maximum intensity projection reconstruction of contrast magnetic resonance angiograms of the systemic veins in a patient who has had a Fontan operation. The images are rotated around a cranio-caudal axis. The imaging plane does not include the anterior part of the right atrium. The inferior caval vein (ICV), superior caval vein (SCV), right atrial to pulmonary artery anastomosis (A) and the right pulmonary artery are seen (RPA). A total of 20 images were obtained that are best viewed as a cine loop.

systems, these images can be acquired at high resolution. This must now be considered the imaging technique of choice for the great arteries and veins (Fig. 2). It is unequalled for the imaging of the pulmonary veins (Fig. 3). Our experience with this technique has been so successful that we now routinely use general anaesthesia for young children to enable breath-holding images to be obtained.

Displaying three-dimensional images of the heart itself is more technically challenging. Firstly, the images have to be acquired in a way that corrects for cardiac motion. This has been possible for some time, but the time required to acquire such large data is long. Because of this, it was not feasible to use the technique clinically. An additional problem has been the very long time required subsequent to acquisition for the data to be transformed into a three-dimensional image that displays the cardiac morphology in a way that can be readily appreciated. Fast magnetic resonance imaging has now made it

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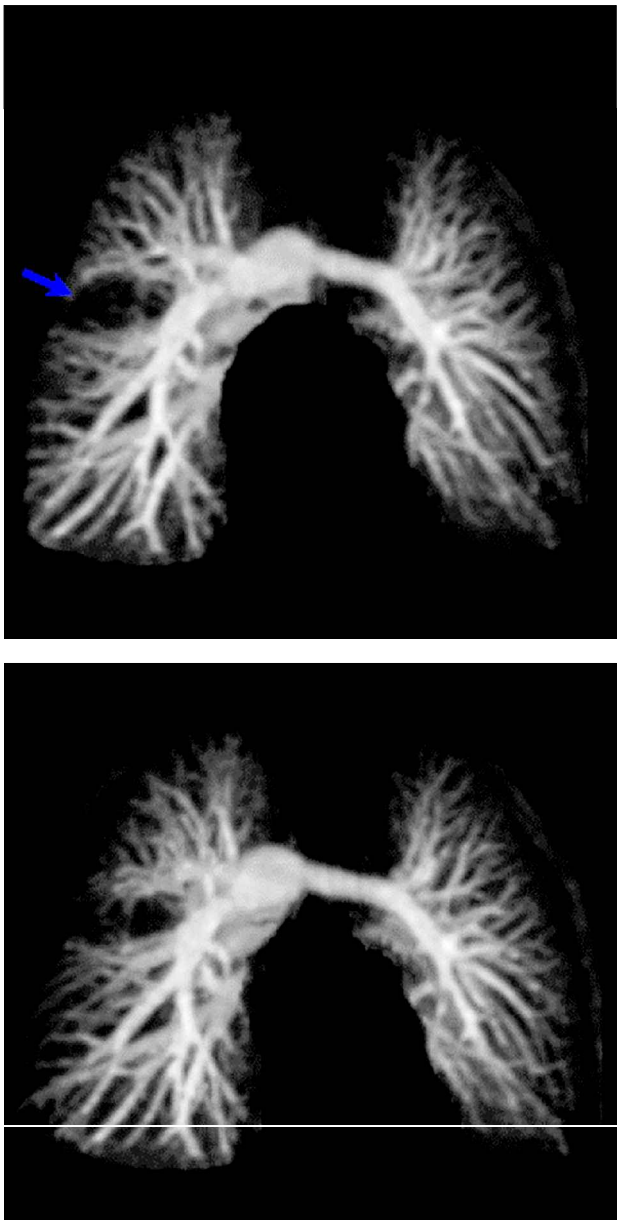


Figure 2.
Two frames from a contrast enhanced magnetic resonance pulmonary angiogram, displayed as a maximum intensity projection. The heart has been removed from the image after acquisition, so that only the pulmonary vasculature is displayed. Both the pulmonary arteries and veins are visible. There is a perfusion defect in the right lung, which may be related to a previous right-sided Blalock shunt (Arrow).

practical to acquire sufficient data for three-dimensional cardiac imaging data in a reasonable clinical time. The so-called "post-processing" is still time-consuming, but increased computing power, and better algorithms for detection of edges, have made this feasible for selected patients.

Cardiac images are typically displayed as a surface shaded display.[7] A virtual light source is

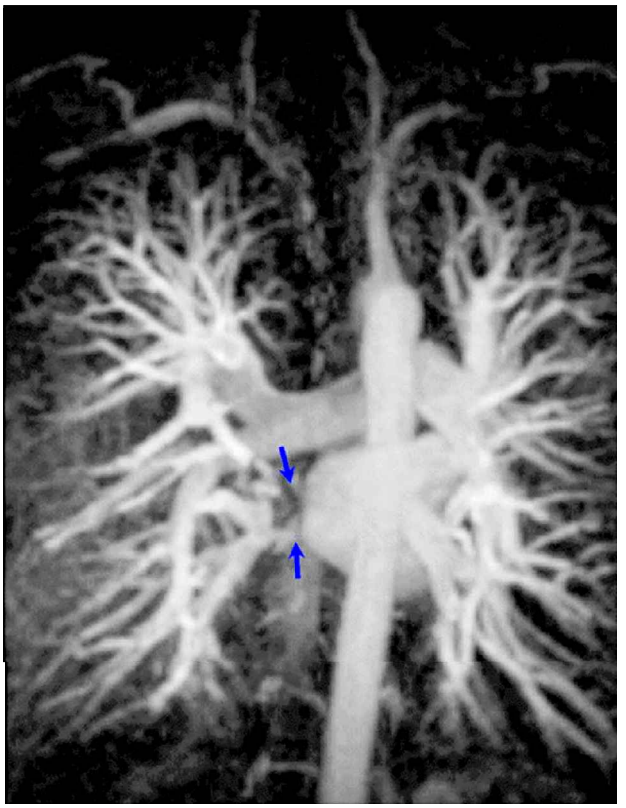


Figure 3.
A single frame, viewed from the front, of a maximum intensity projection of a contrast enhanced magnetic resonance angiogram in a patient with severe post-operative stenosis of the right pulmonary veins. The arrows point to the stenotic segments. In this patient, other imaging methods, including X-ray angiography, had failed to demonstrate this pathology.

computed for each surface, which is shaded to give a three-dimensional effect. Different surfaces can be shaded in different colours to allow them to be distinguished more easily (Fig. 4). An example of a surface rendered three-dimensional image is shown in Figures 5 to 8. Such imaging provides insights into the anatomy of abnormal hearts in life in a way that has never been possible before. For many of the common and straightforward malformations, this may have little impact, but for the more complex anomalies it may prove to be of value in their pre-operative assessment. It is also possible to envisage three-dimensional sets of data of the malformed heart becoming an essential teaching resource, comparable to current pathological collections.

Other imaging protocols

Functional imaging of the heart is now also becoming more rapid and more practical.[8,9] These techniques have been discussed in a previous article,[6]

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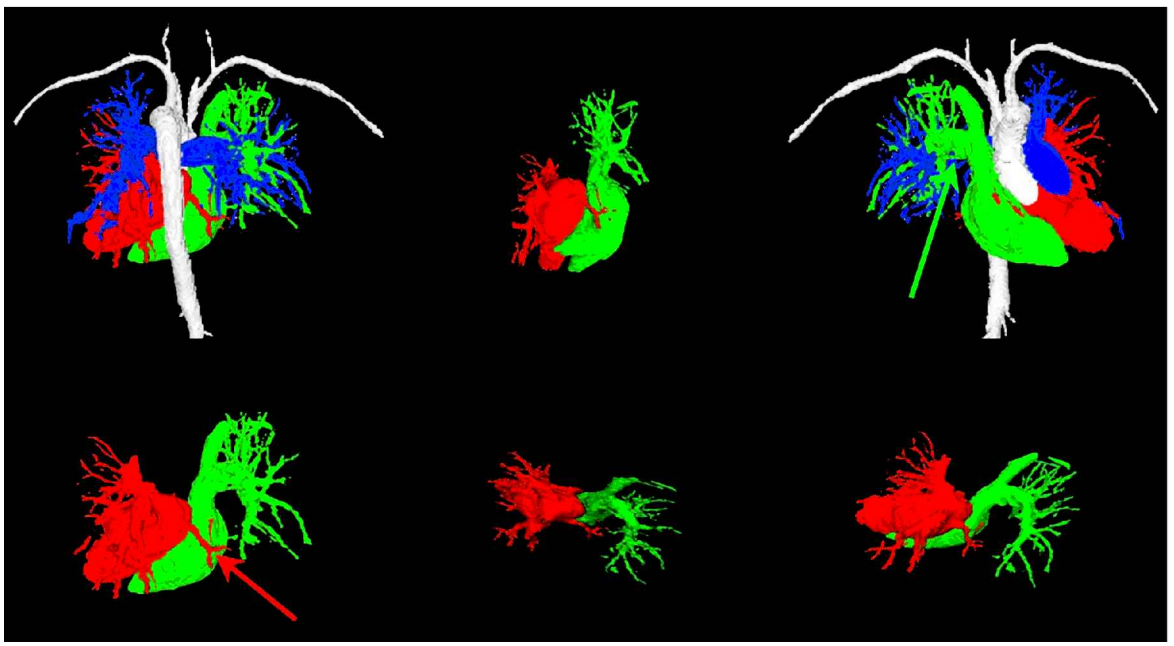


Figure 4.
A three-dimensional reconstruction of a heart with partially anomalous connection of the right pulmonary veins. Different structures have been surface-shaded in different colours. Six views are shown. In two, the aorta (white) and pulmonary arteries (blue) are included. The remainder show only the left atrium and veins draining to it and left ventricle (red), and the right atrium and veins draining to it and part of the right ventricle (green). Most of the right pulmonary veins drain to the superior caval vein (green arrow). One small right pulmonary vein drains directly to the left atrium (red arrow). The left pulmonary veins drain normally to the left atrium.

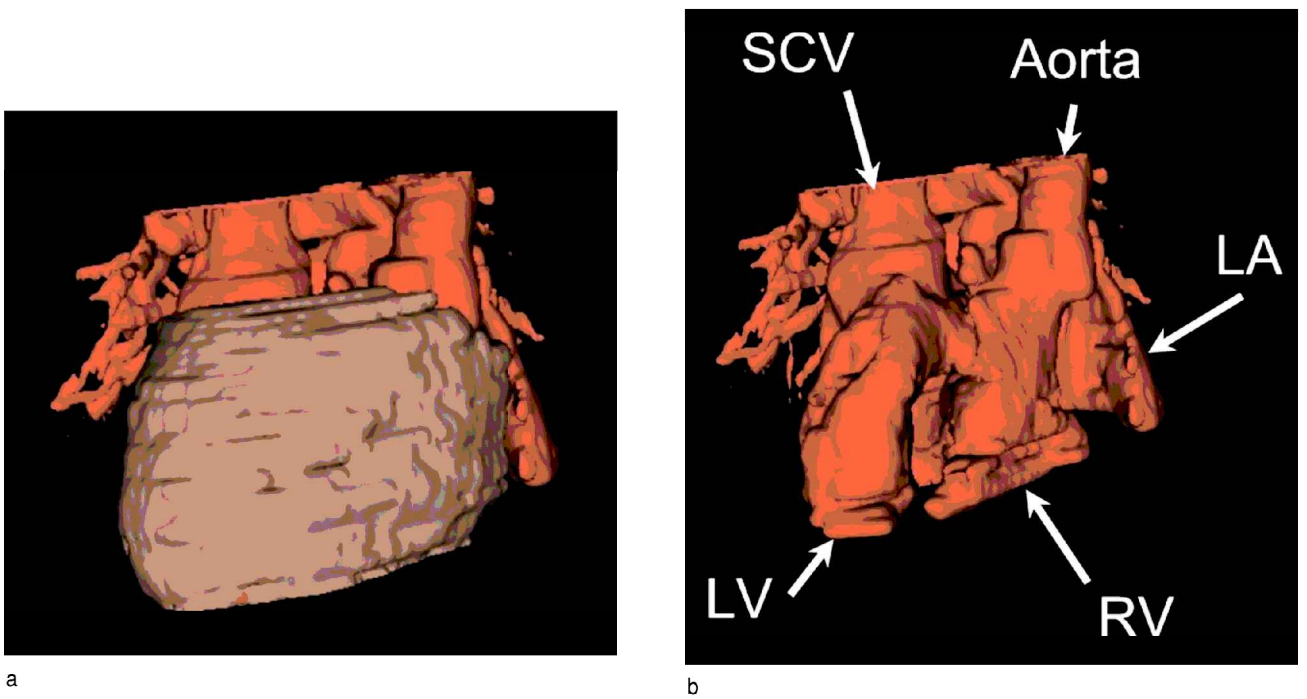


Figure 5.
a: A three-dimensional reconstruction of a heart with usual atrial arrangement, discordant atrioventricular connections, and double outlet from the morphologically right ventricle. The heart is orientated in its anatomical orientation viewed from the front. The epicardial surface of the ventricular myocardium is shaded in grey and the endocardial surface of the heart in pink. The apex of the heart points slightly towards the right; b: The same reconstruction as A, in the same orientation, with the ventricular myocardium removed showing only the endocardial surface of the heart. (SCV = superior caval vein; LV = left ventricle; RV = right ventricle; LA = left atrium)

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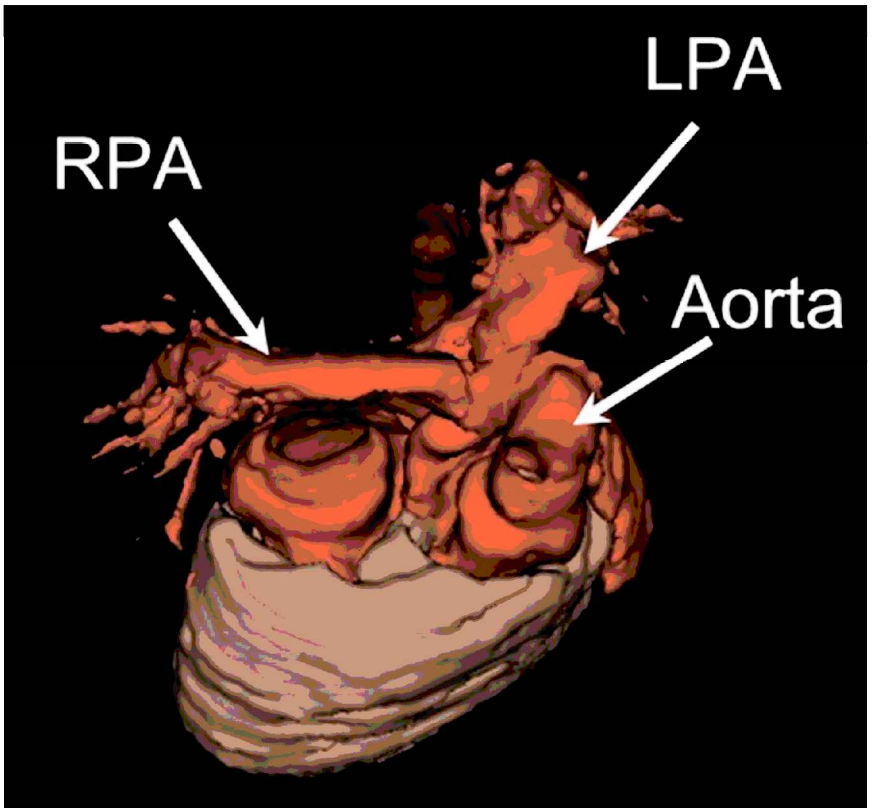


Figure 6.
The same three-dimensional reconstruction as in Figure 5. The image is rotated to view the reconstruction from above. It shows the two great arteries arising from the left-sided morphologically right ventricle. The aorta is to the left and anterior, while the pulmonary trunk is posterior and to the right, and is markedly smaller than the ascending aorta. (RPA Right pulmonary artery; LPA left pulmonary artery).

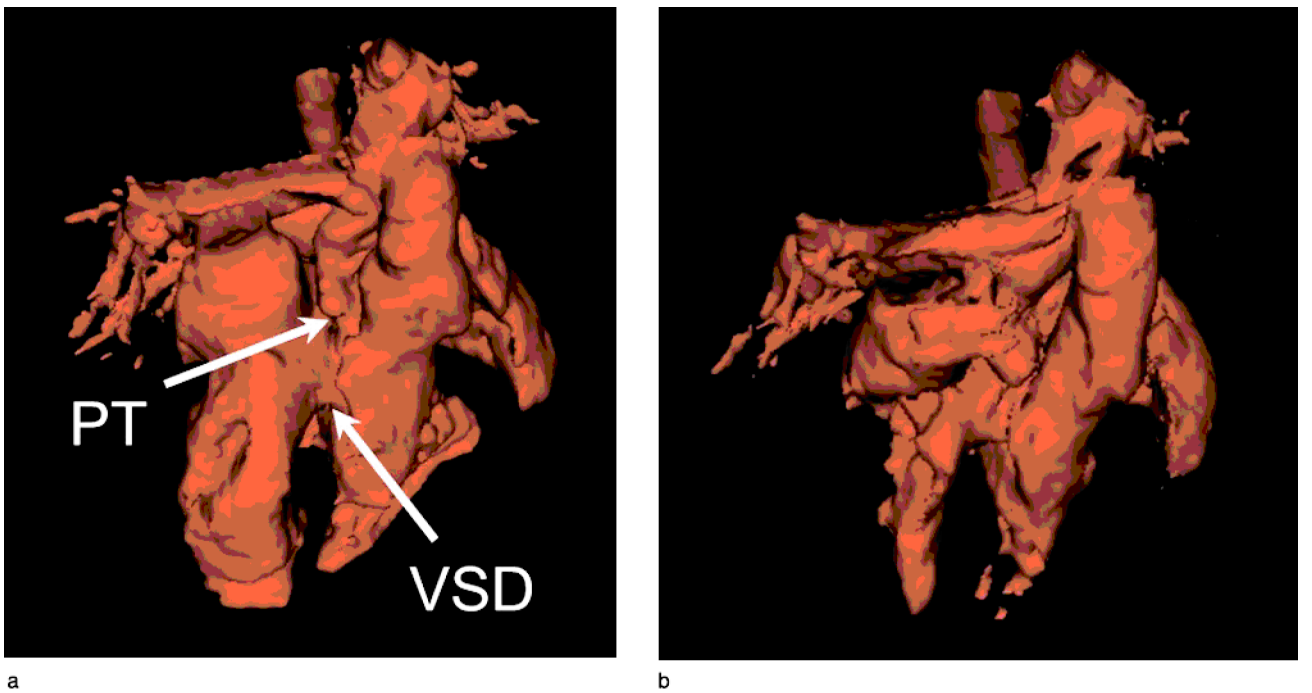


Figure 7.
(a) A diastolic reconstruction of the endocardial surface of the same heart as in figures 5 and 6. The ventricular septal defect is clearly shown (VSD). It is closely related to the origin of the pulmonary trunk (PT); (b) A systolic image of the same view as shown in Figure 7A.

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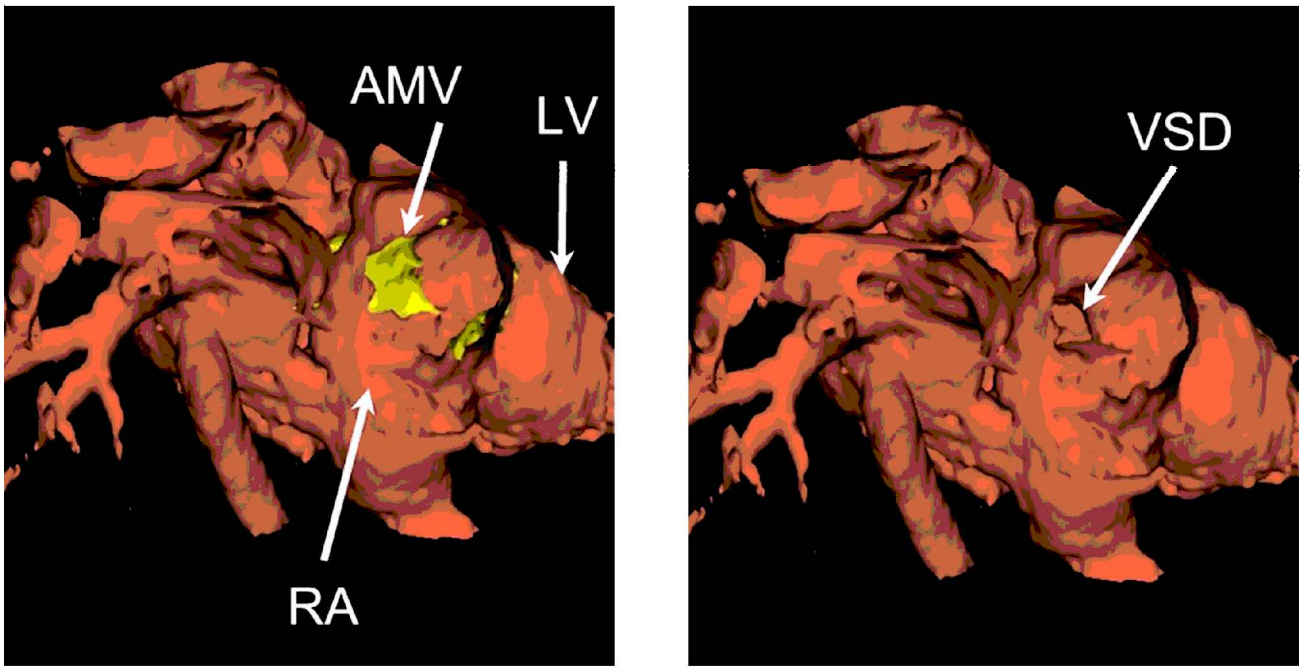


Figure 8.
(a) The same heart as in figures 5, 6 and 7. The endocardial surface is viewed from the right side. The wall of the right atrium (RA) has been removed. Looking into the right atrium, you can see the two leaflets of the mitral valve, in yellow, guarding the opening into the morphologically left ventricle (LV). (AMV – anterior leaflet of the mitral valve); (b) The same view as in Figure 8A, but the mitral valve has been removed to reveal the ventricular septal defect (VSD), which lies immediately behind the anterior leaflet of the mitral valve.

and will not be described in detail here. It is important to understand, nonetheless, that faster acquisition will also have an impact on the utility of functional imaging. For several years, magnetic resonance imaging has been said to be the "gold standard" for the measurement of ventricular volumes, but it has not been a practical reality. Now rapid imaging makes it much more practical. Magnetic resonance can also measure intravascular flow of blood, including shunts. This technique has been well validated, but again time constraints have meant it has not been widely used. This should change. Together with these techniques, new forms of functional imaging are being developed. Principal amongst these is myocardial perfusion imaging, again using gadolinium.[8] Also, and perhaps more relevant to congenital cardiac malformations, are studies of regional abnormalities of wall motion. Other techniques, such as direct measurement of intravascular saturations of oxygen, may also become a reality.[10]

Conclusion

There seems to be little in the way of cardiac imaging of which magnetic resonance imaging is not capable. What has been holding it back has often been practical difficulties rather that technical limitations. These practical difficulties are now being overcome. Cardiac magnetic resonance imaging is likely to have a big impact on clinical practice in the next few years.

Very extensive data can be produced from a single cardiac examination. It is no longer satisfactory to view magnetic resonance images of the heart on static cut films. They are three-dimensional and dynamic. Improvements in, and wider availability of, digital video imaging are important in the understanding of the cardiac and vascular anatomy and in the dissemination of the results of imaging procedures.

In children, magnetic resonance imaging has conventionally been performed using sedation. In our view, this is no longer adequate. We perform all examinations involving magnetic resonance imaging of the heart in children under general anaesthesia. This can guarantee high quality imaging, free of motion artefact, in every patient. It also allows breath-holding scans to be performed in children, which we have found fundamental to obtaining good quality imaging.

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