Cardiovascular MRI in Congenital Heart Disease

An Imaging Atlas
Preface

The last 10 years has seen explosive expansion of the number of centres performing cardiovascular magnetic resonance (CMR) imaging. The majority of this expansion has been in the field of adult ischaemic imaging, but congenital heart disease remains one of the main indications for CMR. Importantly, the greatly improved survival of patients with congenital heart disease gives us a burgeoning adult population living with the sequelae of the disease (grown-up congenital heart disease – GUCH).

Without previous experience or formal training, the interpretation of CMR images of patients with congenital heart disease can be difficult. The main aim of this book is to create a portable resource that offers efficient access to high-quality MR (and where appropriate, CT) images of the common congenital and structural heart abnormalities. We hope that by providing key images for each condition and a clear interpretation of the MR appearances, we will improve the reader’s understanding of the conditions, facilitate their interpretation of images and optimise the planning of the imaging protocols during their own practice of congenital CMR.

As with any publication from a single institution, the contents of this book represent our own practice. We have not written a definitive or exhaustive description of the conditions. However, we hope that we have produced a factual, simple and eye-pleasing guide for fellows training in CMR, radiographers and technicians performing CMR scans, physician users of CMR, and perhaps those few in adult ischaemic practice, who may need the occasional aide memoir for incidental findings!

We hope that you will find this book useful in your everyday practice and learning.

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1 Technical Considerations

Paediatric Challenges
- The usual technical difficulties faced when performing a cardiac MR examination are further amplified when imaging small children
- Optimal image quality may be compromised because of
  - The smaller size of structures
  - Faster heart rates
  - The reduced time for image acquisition (inability or difficulty with breath-holding)
- The imaging protocol should be prioritised to obtain the most crucial diagnostic information, in case the patient’s cooperation is limited

1. Spatial Resolution
Smaller field-of-views (FOVs) and the use of thinner slices are required to image small anatomical structures.

   This leads to increased image resolution, but a corresponding reduction in signal:noise (S/N) ratio. This can be compensated by
   - Increasing the number of acquisitions – (disadvantage: increase in scan time)
   - Removing parallel imaging features – (disadvantage: increase in scan time)
   - Using a coarser matrix, to increase diagnostic image quality, albeit at the cost of reduced resolution

2. Appropriate Coil Selection
Appropriate coil selection is important to maximise S/N ratio.
   - A dedicated extremity (knee coil) should be used in neonates or very small children.
   - A transmit/receive coil can reduce noise and increase S/N ratio.
   - If the child is too large for this, then a body matrix and spine coil combination achieves good results.

3. Faster Heart Rates
Faster heart rates in small children result in a short R-R period.
   - For sequences where repetition times (TR) are longer than the R-R period, gating, using the second or third R wave as the trigger facilitates more time for the appropriate recovery of longitudinal magnetisation.
   - For cine-imaging, reducing the number of phase encode steps in each frame will decrease the acquisition period for each frame, improving temporal resolution and image sharpness. However, this increases scan times.

4. Strategies to Reduce Motion Artefact
- Play therapy or pre-examination visits to the scanner can help a child overcome any anxiety and improve in-magnet stillness.
- Installing a DVD/Video system is a worthwhile investment to promote prolonged distraction and cooperation.
- For children who have difficulty breath-holding, images can be acquired during free breathing. Additionally:
  - Use manual shimming techniques, as they are essential to minimise flow artefacts, particularly on balanced SSFP sequences
  - Increase the number of acquisitions (NEX) from 1 to 3
  - Use respiratory compensation methods to acquire data, e.g. use of navigator echoes, phase re-ordering algorithms.
  - Acquire data using real time imaging sequences (where imaging systems allow).

5. Contrast Administration in Children
For angiography, we use 0.2–0.4 mL/kg of Dotarem, (Guerbet, Paris) which corresponds to 0.1–0.2 mmol/kg. All Gadolinium contrast agents need to be given in accordance with Institutional and National guidelines to avoid nephrogenic systemic fibrosis (NSF). For further information on this, see the UK Royal College of Radiologists document on this subject: http://www.rcr.ac.uk/docs/radiology/pdf/BFCR0714_Gadolinium_NSF_guidanceNov07.pdf

6. Consider Alternative Imaging Strategies
CT is potentially useful if MR assessment is limited or hampered by technical restraints.
Indications for General Anaesthesia (GA) for Paediatric MR
Practice varies throughout the world. However, most centres in the UK will perform cardiovascular MR under general anaesthetic (GA) for children under the age of 7 years.

General Safety Issues Specific to Paediatric Cardiac Imaging
- Patient metal checked and the safety questionnaire performed with parents before the child is anaesthetised.
- Senior cardiac anaesthetist continuously present in every case.
- Full monitoring: pulse oximetry, end-tidal gas analysis, ECG and non-invasive BP.
- Wrap the patient in gamgee or blankets to keep him or her warm.
- Ten metre circle breathing system needed, to link the patient to anaesthetist in MR control room.
- Breath-holding in passive expiration, controlled by breaking the circuit in the control room.
- The large dead space prohibits low flow anaesthesia.
- Reversal of anaesthesia and extubation in CMR induction room. Ensure that the team is aware of the cardiac arrest procedure.
Importantly, the child MUST be withdrawn from the MR room for resuscitation. Metallic objects such as resuscitation trolley MUST NOT be brought into the scanning room.

Environmental and Physical Constraints
Performing general anaesthesia (GA) in a magnetic resonance (MR) environment is challenging for many reasons
- During the scan, there is limited access to the child and ventilation equipment.
- Care is required for staff and patient safety with regard to ferromagnetic equipment.
- There is a potential for RF interference with monitoring equipment.

Technical Factors Specific to MR in Infants and Small Children
- Prolonged, multiple breath holds are required. This can cause hypoxia. Adequate pause for ventilation control between breath holds is required.
- A reliable ECG is vital for gating during image acquisition.
- Monitor patient temperature closely. The low ambient temperature in MR scanning room produces a hypothermia risk, particularly for small infants.

Fig. 2.1. Photography showing one of our dedicated paediatric cardiac MR labs. Inset, control room with monitoring equipment and long anaesthetic tubing to enable the anaesthetist to sit in the control room during MR scanning.
### Table 3.1 Suggested imaging protocols for given conditions

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Vent cines</th>
<th>CE-MRA</th>
<th>Flow</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shunts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASD, SVD, AVSD, VSD</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
<tr>
<td><strong>Valvar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS, AI, MR, MS</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
<tr>
<td><strong>Aorta</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarctation, rings and slings, Marfan</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
<tr>
<td><strong>RVOT/PA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS, ToF, PA, TGA, truncus</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Cardiomyopathy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCM, DCM, non compaction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
<tr>
<td><strong>Coronary arteries</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anomalous, ALCAPA, Kawasaki</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
<tr>
<td><strong>Complex CHD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DORV, DILV, CCTGA, HLHS, BCPC, Fontan, TCPC, Ebstein</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>±</td>
</tr>
</tbody>
</table>
### Table 3.2 Imaging protocol (standard sequences and views in the order of workflow)

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Planning</th>
<th>1° Purpose</th>
<th>2° Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scout</td>
<td>Single shot bSSFP images</td>
<td>3 Images in all 3 orthogonal planes</td>
<td>Iso-centering of the heart in the scanner</td>
</tr>
<tr>
<td>Axial stack</td>
<td>Respiratory-navigated, ECG-gated, “black-blood” images (HASTE or TSE). Contiguous axial slices</td>
<td>Coverage from liver to neck</td>
<td>Planning subsequent cine imaging planes</td>
</tr>
<tr>
<td>Ventricular long-axis (RVL/LVLA)</td>
<td>Breath-held, ECG-gated, bSSFP cine images</td>
<td>From axial stack</td>
<td>Planning the true 4-chamber image</td>
</tr>
<tr>
<td>AV valves</td>
<td>Breath-held, ECG-gated, bSSFP cine image</td>
<td>From AV valves view</td>
<td>Planning the 4-chamber and LV outflow tract (LVOT) images</td>
</tr>
<tr>
<td>4-Chamber view</td>
<td>Breath-held, ECG-gated, bSSFP cine image</td>
<td>From AV valves view</td>
<td>Subjective assessment of atrial size, biventricular size &amp; function, ventricular wall motion, AV valve regurgitation</td>
</tr>
<tr>
<td>SA stack</td>
<td>Breath-held, ECG-gated, bSSFP cine image</td>
<td>From end-diastolic frame of 4-chamber cine</td>
<td>Provides the images required for segmentation of ventricular volumes</td>
</tr>
<tr>
<td>Sequence</td>
<td>Planning</td>
<td>1° Purpose</td>
<td>2° Purpose</td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>MR angiography</strong></td>
<td>Breath-held, not ECG-gated Gadolinium injection 0.2–0.4 mL/kg Infants: injection rate 2 mL/s with 5 mL flush. Older children: injection rate 3 mL/s, 10 mL flush</td>
<td>Isotropic voxels (1.1–1.6 mm). Planned on axial HASTE stack, for coronal-orientated raw data. Include antero-posterior chest wall and lungs. Image acquisition triggered with bolus-tracking to ensure maximum signal in structure of interest. Two acquisitions routinely acquired, with no interval in young children, or a 15 s interval in older children</td>
<td>Angiographic views of large and small thoracic vessels. Images less subject to artifact caused by low velocity or turbulent flow. The second pass acquisition allows assessment of systemic and pulmonary venous anatomy</td>
</tr>
<tr>
<td><strong>3D bSSFP</strong></td>
<td>Free breathing, respiratory navigated, ecg-gated. Data acquisition optimised to occur in diastole. Signal improved following gadolinium injection &amp; in tachycardic pts by triggering acquisition every second beat. Acquisition time 8–15 min</td>
<td>Planned on axial HASTE stack for sagittal orientation of raw data. Isotropic voxels (1.1–1.6 mm). Respiratory navigator placed mid-right dome of diaphragm, avoiding cardiac region of interest</td>
<td>Provides high-resolution images of intracardiac anatomy, including coronary arteries. Allows multiplanar reformatting</td>
</tr>
<tr>
<td><strong>LV outflow tract</strong></td>
<td>Breath-held, ECG-gated, bSSFP cine image</td>
<td>From the AV valves cine. Place a perpendicular plane through basal aortic valve and mid-mitral valve orifice. Check that orientation passes through LV apex using LVLA cine. Cross-cut this view to obtain two orthogonal cine views of LVOT</td>
<td>Outflow tract morphology. Subjective assessment of semilunar valve function</td>
</tr>
<tr>
<td><strong>RV outflow tract</strong></td>
<td>Breath-held, ECG-gated, bSSFP cine image</td>
<td>From axial stack. Place perpendicular plane through the pulmonary trunk. Cross-cut this view to obtain two orthogonal cine views of RVOT</td>
<td>Outflow tract morphology. Subjective assessment of semilunar valve function</td>
</tr>
<tr>
<td><strong>Great vessel flow</strong></td>
<td>Non-breath held, ECG-gated Through-plane phase contrast velocity mapping</td>
<td>From the orthogonal outflow tract images. Place a perpendicular plane across the vessel of interest. Place plane just distal to valve leaflets in systole, to avoid turbulent areas of flow. Optimise velocity encoding to maximize accuracy and prevent aliasing</td>
<td>Vessel flow volume. Calculate regurgitant fractions (RF%). Validate ventricular stroke volume measurements</td>
</tr>
</tbody>
</table>
4 Normal Anatomy-Axial

The transverse or axial plane is useful for studying morphology and the relationships of the four cardiac chambers and the pericardium.

Images (a) through (f) show axial planes in a head to foot direction.
Normal Anatomy-Coronal

Frontal or coronal images are most useful for investigation of the LVOT, of the left atrium, and the pulmonary veins.

Images (a) through (f) show coronal planes through the heart in an apex-to-base direction.