The future series . . . CMR discussed by Matthias G Friedrich

The Future of Cardiovascular Magnetic Resonance Imaging

Cardiovascular imaging is an essential component of the diagnostic investigations in clinical cardiology. Imaging is ALSO a major cost factor in medicine; thus, for selecting an imaging technique, an individual, informed decision must be based on accessibility, safety, diagnostic accuracy, cost, and its added value to therapeutic or preventive decision-making. Current imaging techniques use a large range of the electromagnetic frequency spectrum to acquire information:

• Echocardiography (7–12 MHz)
• Magnetic resonance imaging (64–128 MHz)
• Computer tomography (>30 000 000 000 MHz)
• Nuclear cardiology including single-photon emission computed tomography (SPECT) and positron emission tomography (PET) (>10 000 000 000 000 MHz)

Cardiovascular magnetic resonance and its evolving role in clinical cardiology

Current imaging techniques use different physical principles and diagnostic targets (see Table 1). CMR makes use of the phenomenon that virtually all molecules have specific relaxation properties after a low-energy radiofrequency pulse and therefore does not require radiation unlike CT or radioactive material as nuclear cardiology. Its spatial resolution is better than that of the nuclear scans and its image quality is more consistent than that of the echocardiography.

Cardiovascular magnetic resonance (CMR) allows for gold standard level quantification of volumes and flow. CMR first-pass perfusion has been shown to at least match the diagnostic accuracy of SPECT. CMR also has the highest native tissue contrast and thereby contrast agents are not always necessary. Myocardial tissue characterization has emerged as the most important non-invasive tool in the diagnostic investigation of cardiomyopathies, especially myocarditis, iron overload, and amyloidosis. CMR is the only non-invasive technique to demonstrate myocardial oedema and iron overload. Finally, CMR clearly stands out because of its versatility and the unmatched breadth of information obtained from a single scan.

Important recent developments shaping the future of cardiovascular magnetic resonance

Magnetic resonance imaging systems and coils

Following improvements in magnet and helium handling technology, stronger gradient systems, and higher field strengths have allowed for an increased contrast-to-noise ratio for several applications, especially perfusion, contrast-enhanced tissue characterization, and angi-

Table 1 Imaging techniques in clinical cardiology: basic contrast-generating principles and diagnostic targets

<table>
<thead>
<tr>
<th>Technique</th>
<th>Basic principle</th>
<th>Relevant diagnostic targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echocardiography</td>
<td>Reflection of ultrasound waves</td>
<td>Cardiac anatomy, wall motion, valvular motion, flow velocity, and contrast media inflow</td>
</tr>
<tr>
<td>CMR</td>
<td>Magnetic behaviour (relaxation) of protons in blood and tissue</td>
<td>Cardiac anatomy, wall motion, volumetric, flow velocity, tissue pathology, and vascular anatomy</td>
</tr>
<tr>
<td>CCT</td>
<td>X ray permeability of tissue</td>
<td>Cardiac anatomy, calcification, and vascular anatomy</td>
</tr>
<tr>
<td>Nuclear cardiology</td>
<td>Gamma ray emission of injected radioactive tracers</td>
<td>Metabolic activity</td>
</tr>
</tbody>
</table>

CCT, cardiac computed tomography; CMR, cardiovascular magnetic resonance.
ography. Coil technology has benefitted from novel surface coil concepts with more channels and a massive increase of data points, which can be used for increasing spatial resolution, temporal resolution, or signal-to-noise.

Workstation and user interface
More and more, fast Graphics Processing Units (GPU) are used for accelerated image reconstruction instead of Central Processing Units (CPU).

In comparison with other imaging modalities, magnetic resonance imaging (MRI) has many more adjustable parameters and a wider range of imaging options. Therefore, special attention must be paid to system operations. Recently, the industry has intensified the development of more intuitive user interfaces and workflows, including automated algorithms for identifying anatomical axes of the heart or even the entire scan procedure. Such advances, where used, have enabled less experienced staff to acquire diagnostically useful CMR images. Furthermore, software for a time-efficient post-processing, evaluation, and reporting of data are increasingly facilitating the work for readers.

Morphology and function
Accelerated or parallel image acquisition such as compressed sensing can shorten scan times by a factor of 10 or more,2 with complete 3D cine imaging of the ventricles in one single breath-hold (Figure 1).

Novel analysis methods (feature-tracking or tissue-tracking) allow for measuring strain, strain rate, torsion, and twist in post-processed regular cine images, thereby not adding additional scan time (Figure 2).

Faster computing algorithms have also facilitated handling of large flow data sets with calculation of time-resolved 3D data, also dubbed 4D flow (Figure 3). Flow patterns and quantification provide information on flow volumes, turbulence, and shunts.5 This is especially interesting for CMR assessment in patients with complex congenital heart disease.

Protocols
Driven by the Society for Cardiovascular MR (SCMR) and partners such as the CMR Section of the European Association for Cardiovascular Imaging, protocol standards and evaluation procedures for CMR have been published and are regularly updated.4,5 In typical clinical settings, focused protocols facilitate an efficient workflow, allowing for scan times of less than 30 min even for scans with pharmacological vasodilation.6 In a recent landmark study performed in Bangkok, 123 CMR scans for the assessment of ventricular function and myocardial iron load were performed within 24 work hours,7 demonstrating the potential of optimized workflows in state-of-the-art CMR.

Tissue
After more than a decade of development, parametric myocardial mapping of myocardial relaxation times is rapidly entering clinical application. The technique provides direct measurement of relaxation times instead of signal intensity values and thus further improves the capabilities of CMR to perform a non-invasive assessment of myocardial pathology in vivo.8 For acute myocarditis, cardiac amyloidosis, iron overload, and Fabry’s disease, native (i.e. without contrast agents) mapping including the measurements of the extracellular volume is already robust enough to be used for clinical decision-making. Figure 4 gives an example.

MR Fingerprinting (MRF) uses randomly acquired data points and pattern recognition algorithms to generate parametric maps for proton density images and T1/T2 maps.9 Optimized T1-weighted sequences have been shown to identify unstable plaques and therefore add an important missing piece to the diagnostic evaluation of coronary artery disease. While still scarce, published data indicate an outstanding potential for identifying plaques at risk.10

Dynamic tissue analysis
Native T1 mapping before and during vasodilator infusion has been successfully applied to track myocardial perfusion,11 alleviating the
need of contrast agents for perfusion imaging. Importantly, such dynamic studies using quantitative data are less sensitive to systematic confounders.

Very recently, oxygenation-sensitive CMR (OS-CMR) has emerged as a disruptive technology for monitoring changes of markers for myocardial oxygenation without the use of contrast agents. The combination with CMR-derived markers for perfusion and metabolism leads to an unprecedented power to examine all levels of myocardial pathophysiology. OS-CMR has also already demonstrated the ability to assess for microvascular dysfunction and for the detection of inducible myocardial ischaemia in patients with significant coronary artery stenosis (Figure 5).

### Interventional

Several labs in the USA and in Europe have already started using CMR for invasive vascular applications such as catheterization of the pulmonary arteries. Interventional CMR opens the door to radiation-free vascular procedures, including the quasi-simultaneous assessment of myocardial tissue characteristics via catheter-mounted receive coils during electrophysiology interventions. In the future, even coronary interventions in an MRI system may become feasible.

### Big data

CMR-derived continuous data on morphology, function, tissue, and metabolism can easily be transferred to large data bases. The SCMR has already initiated a global CMR registry which will have the possibility to store mass imaging data for further analyses. Once issues around data ownership, patient privacy, digital formats, inter-system communication, and access are addressed, such large data sets will not only allow for collecting cases of rare diseases, but also help to develop advanced diagnostic methods. Machine learning including deep, structured learning algorithms in such dynamic data sets for example, could help to identify disease ‘signatures’. The accuracy and precision of CMR renders it an ideal candidate for this strategy.

### Challenges

Access to scanners and reimbursement are often subject to competition between radiologists and cardiologists. This typically leads to poor local CMR service with limited image quality and less useful
results, eventually leading to limited access for patients to state-of-the-art diagnostic procedures. Inefficient and complex interfaces of MRI systems discourage MRI system owners to use the system for cardiovascular applications. Long scan times affect both patients and technologists and lack cost-efficiency. In many countries, the cost for contrast agents is prohibitive and appropriate contrast-enhanced protocols are infrequently used.

Cardiovascular magnetic resonance of the future

Decades of technical developments have generated a breath-taking world of CMR techniques with gold standard level approaches for analysing morphology, function, tissue, and metabolism (see Table 2). Most of them have been extensively tested for validity, accuracy, and impact on clinical decision-making. Less and less protocols will require contrast agents as novel techniques such as mapping and dynamic OS-CMR become available. New coil concepts, such as coil system with transmit/receive functionality will significantly improve the available signal-to-noise ratio per pixel. In addition, researchers, MRI industry, and software companies are more efficiently addressing clinical workflows and cost efficiency.

Industry has realized that MRI systems are often benchmarked by their ability to perform CMR, and that the CMR markets are growing fast, with expected large-scale clinical application world-wide, especially in highly populated countries with an increase of cardiovascular disease. This will lead to more efficient, dedicated CMR system environments with largely automated image acquisition, evaluation, and reporting.

Outsourcing of image data management including image reconstruction as well as post-processing, evaluation, and interpretation will be possible through cloud-based services. This is already in practice for other imaging procedures (e.g. offshore 24/7 chest X-ray interpretation), but, especially when combined with remote expertise, will be specifically important for CMR in mid-sized and small institutions. It will be possible to store data for offline analysis in large data bases and continuous machine learning will help improving our understanding of disease and be a cornerstone in the development of novel, meaningful, and cost-efficient diagnostic approaches.

CMR is on its way to become the cardiac imaging modality for all questions not readily answered by history, physical exam, and a portable echocardiogram. Following this evolution and its positive impact on our patients is exciting and for those actively involved in the field, very gratifying.

Conflict of interest: none declared.

References

References are available as supplementary material at European Heart Journal online.