Clinical research has clearly indicated the power of cardiac magnetic resonance (CMR) imaging for the diagnosis, treatment and monitoring of cardiac disease [1]. It has been shown that CMR imaging allows the inspection of a plurality of aspects, amongst which the anatomy of the heart and surrounding blood vessels, myocardial (heart muscle) contraction and resulting ventricular pump function, myocardial perfusion and viability, and ventricular and vascular blood flow. A brief description of CMR imaging is given below in the section on the State of the Art.

CMR imaging research has focused on applications for patients with coronary-artery-stenosis induced ischemia and infarction [2, 3]. However, research on imaging of other cardiac diseases is also ongoing. Thanks to its lack of ionizing radiation, CMR imaging is a preferred modality for congenital heart disease patients, who are often imaged many times during their life [4]. CMR imaging is also under investigation for electrophysiological disorders such as atrial fibrillation and ventricular tachycardia [5].

All major medical imaging equipment manufacturers and several software companies offer software for the quantitative analysis of CMR images. The quantitative information that can be derived ranges from global parameters such as ejection fraction to detailed local myocardial wall thickening. Philips offers the ViewForum MR Cardiac package, with which myocardial function, perfusion and viability, as well as ventricular and vascular blood flow, can be visualized, quantified and reported [6].

After years of intensive research, CMR imaging is now on the eve of being accepted and used more frequently in daily clinical routine. The Current Procedural Terminology (CPT®) Editorial Panel of the American Medical Association has recently issued eight new codes for the reimbursement of CMR imaging [7]. Although this may stimulate a broader application, the use of CMR in daily clinical routine is still hampered by the lack of well-trained personnel and the limited efficiency and ease-of-use of the imaging equipment and image analysis software [8]. Basically, one could say that CMR-based cardiac care is already effective, but its ease-of-use still needs to be improved significantly.

This article focuses on quantitative analysis, especially for the diagnosis of coronary artery disease. The section on Task Guidance below explains how the ease-of-use could be enhanced, and consequently the amount of training reduced, by introducing dedicated task guidance.

The section on Automation argues that the efficiency and reproducibility could be significantly improved by performing as much of the analysis as possible automatically, using dedicated image-processing techniques. The section on Comprehensive Visualization explains that the comprehensive representation of the many quantitative results in a single 3D visualization will significantly simplify the interpretation of the results. We also offer a section on Reporting which focuses on the reporting of analysis results, and a section on Future R&D that presents our vision of the future research that is considered to be essential for achieving broader acceptance of CMR in routine clinical practice.

State of the art

For patients with suspected coronary artery disease, a CMR examination typically consists of multiple image acquisitions (series or scans) serving different purposes [9]: functional CMR scans to assess the myocardial pump function, perfusion CMR scans to localize reduced blood supply to the myocardium, and viability CMR scans to localize infarcted myocardial tissue.
A growing number of whole-heart scans are also being made, in order to inspect the anatomy and function of the ventricles and especially of the coronary arteries (Figure 1).

**Functional CMR scans**
For functional CMR scans, “cine protocols” are used to acquire movies of the beating heart. These movies consist of 25 - 50 phases and can be obtained in different slice orientations. Typical slice orientations are short-axis (SA, 3-15 slices), 2-chamber long-axis (LA 2CH, 1 slice), 3-chamber long-axis (LA 3CH, 1 slice) and 4-chamber long-axis (LA 4CH, 1 slice).

Functional CMR images are used for the quantification of global volumetric properties (stroke volume, ejection fraction, cardiac output, etc.) and local myocardial wall properties (wall thickness, wall thickening, wall motion, etc.).

In Dobutamine Stress Magnetic Resonance (DSMR) examinations, functional CMR scans are made at increasing levels of pharmacologically induced stress. These examinations are used to detect stress-induced wall motion abnormalities, which are an indication of ischemia and may predict the presence of coronary artery stenoses [10].

**Perfusion CMR scans**
Perfusion CMR scans are usually obtained in only three short-axis view slices. The myocardium of the left ventricle is imaged during the first passage of a Gadolinium-based contrast agent. The use of ECG triggering “freezes” the motion of the beating heart, making it possible to recognize and quantify regional differences in contrast agent uptake, which are shown as changes in the image intensity [2].

**Viability CMR scans**
Viability CMR scans are made 15-20 minutes after the Gadolinium contrast injection. It has been found that the percentage of remaining contrast agent is higher in infarcted regions [11]. Quantitative assessment of myocardial viability involves measurements of infarct size/volume, infarct transmurality and of the remaining healthy tissue.

**Whole-heart CMR scans**
Whole-heart CMR scans typically contain 150 - 200 transverse slices covering the complete heart and the coronary arteries [12]. They are primarily used to relate the coronary-artery anatomy to diseased myocardial regions.

**Task guidance**
Current users of the CMR analysis applications are cardiologists, radiologists and technicians working mainly in academic hospitals. In this environment, the application is often being used to support research into new procedures and techniques. Consequently, until recently, the principal challenge has been to provide leading edge algorithms and functionality.

However, there is now a clearly discernible trend towards more routine use of CMR imaging and analysis. This means that CMR will become more common in community hospitals where throughput has high priority. The time needed from request to report has to be as short as possible without compromising the quality of the analysis results. In this environment, there will be many more users. Also, technicians may rotate jobs more, and the time available to be trained or read user documentation might be less. New and returning users need to be able to get “up and running” as soon as possible.

To allow application in clinical routine, CMR analysis has to become much simpler. To address this problem, we set up a team comprising representatives from industry and healthcare professionals. Our team adopted two main lines of approach. Firstly, we minimized the amount of interaction needed, through judicious use of automation. This is described below in the section on Automation. Secondly, we designed a user interface that better reflects the users’ way of working. This involved restructuring the global user interface and introducing task guidance. Globally, the user interface is now...
structured around distinct activities which the users will recognize in their routine working procedure:
- CMR examination selection (from a work list)
- preparation
- viewing
- analysis
- reporting.

Preparation
During preparation the user selects the image series to be viewed and/or analyzed and, if the series could not be automatically characterized, adds labels to the series that describe the type of acquisition (function, perfusion, viability, etc.), the scan orientation (short-axis, long-axis, etc.) and the stress level. By spending a small amount of time preparing the examination in this way, much more time is saved later on during the core activities of viewing, analysis and reporting.

Viewing
During viewing the user inspects the images using powerful preset viewing protocols and an appropriate set of image viewing tools. Smart linking of e.g. image contrast/brightness, image locations and cine movie speed is part of the viewing protocols. During viewing, the user already has the possibility to type in observations which will later on appear in the report.

Analysis
After viewing, different types of analysis can be performed. For example, a user may choose to do a functional analysis followed by a viability analysis. In our approach both these analyses can be open at the same time, enabling the user to navigate between them with a single click. This will simplify the interpretation of the analysis results.

Reporting
Finally, during reporting the user can manage the observations and/or quantitative results that were generated during viewing and analysis and can summarize them into a report.

The user interface
In the user interface, the activities are represented by a horizontal line of buttons across the top of the application (Figure 2a) similar to the main navigation bar on many web pages. Within each of the activities a list of tasks can be executed. In software engineering terms, these can be seen as use-cases [13]. For each task, the user is guided by a vertical task panel on the left-hand side of the user interface. Each task is related to a specific goal, for example “segment the left ventricle”.

Figure 2. The user interface.

Figure 2a. Overall structure of the user interface. This example shows left ventricle segmentation in short-axis functional analysis.

Figure 2b. Task guidance for LV segmentation in short-axis functional analysis.
A task consists of one or more task steps and the buttons within each of the task steps are the individual *functions* that need to be used. The task panel only shows the functions directly related to the selected task.

Figure 2b shows a zoomed version of the task guidance for short-axis analysis functional analysis. The Figure shows the task steps and functions that have to be performed for segmenting the left ventricle. The list of tasks comprises:

- segmentation of the left ventricle
- segmentation of the right ventricle
- display of the quantitative analysis results.

**Automation**

**The need for automatic segmentation**

Diagnosis based on quantitative analysis results may involve the delineation of up to 3,500 myocardial contours. Manual delineation is too cumbersome and time consuming for daily clinical routine. Moreover, the myocardial contours in one image type, e.g. functional CMR, indicate the same anatomical structures, e.g. the left ventricle, as in the other image types (perfusion, viability). Repeated delineation of the contours in the different image types therefore seems to be a waste of effort.

In daily clinical practice, fast automatic contour delineation is therefore a prerequisite. In this section we briefly introduce four new algorithms for automatic segmentation of the myocardium:

- functional CMR segmentation
- DSMR segmentation
- viability CMR segmentation
- whole-heart and coronary-artery segmentation.

**Functional CMR segmentation**

Due to its multi-slice and multi-phase nature, an SA functional analysis can easily require the delineation of up to 1,500 contours. Consequently, the most significant efficiency improvement can be obtained by automating this delineation task.

Our new SA functional segmentation method consists of two steps. First, the myocardial end- and epicontour are automatically detected for the end-diastolic (ED) phase, using the new algorithm described below. Then, these contours are automatically propagated to the other phases in the cardiac cycle, using the propagation method described by Hautvast et al. [14].

The new automatic ED contour detection algorithm first roughly localizes the LV in a two-step approach. First, a region of interest is determined based on the local image intensity variation over time. Then, a ring detection algorithm capable of detecting the dark myocardium localizes the LV within that region. The detected ring is used to initialize a geometric template that models the myocardium as a closed ribbon structure, composed of an imaginary centerline and a variable width. This model is adapted to the image in a coarse-to-fine approach, until the final delineation is obtained (Figure 3).

In a validation study on 119 clinical SA cine CMR data sets, the LV endo- and epicardial contours were positioned with Root Mean Square (RMS) errors of $1.51 \pm 0.77$ mm, and $1.79 \pm 0.88$ mm, respectively [15].

In the same study it was found that propagation of the automatically detected ED contours results in end-systolic (ES) contours that are as accurate as the ES contours that resulted from the propagation of manually delineated ED contours. More importantly, on a subset of 10 data sets, it was found that users need significantly less time to verify and correct fully automatically detected end-diastolic contours ($28.7 \pm 23.8$ s per slice) than they need for drawing these contours ($44.5 \pm 31.7$ s per slice).

**DSMR Segmentation**

It might be assumed that the contours on all images of all stress levels in a DSMR examination could be easily obtained by re-using the SA functional CMR contour detection algorithm described earlier. This algorithm has, however, been optimized for functional images at rest. It does not perform well enough at the higher stress levels due to the large variations in LV shape and contraction present at these levels. As a result, the time required to manually correct propagated contours and the size of corrections increase with increasing stress level (Figure 4a). Furthermore, the accuracy of the automatic ED contour
detection algorithm decreases with increasing stress level.

For the segmentation of DSMR images, we have developed a dedicated algorithm that is capable of propagating automatically generated contours from one stress level to another. The algorithm consists of a combination of image registration, contour propagation and contour averaging techniques [16]. As a result, the user no longer needs to correct the same delineation error at each stress level. Moreover, the size of corrections no longer increases with the stress level. This saves a substantial amount of time (Figure 4b).

Viability CMR segmentation

The viability imaging protocol is optimized to maximize contrast between healthy and infarcted myocardial tissue. The contrast between infarcted tissue and the left-ventricular blood pool is however often very limited or even totally absent. This makes automatic segmentation of LV myocardial contours in viability images a particularly difficult task.

We have developed a method that uses the LV contours detected in the functional CMR images as a shape prior to viability segmentation. These contours are used to construct a 3D mesh representing the LV. The segmentation algorithm starts by roughly localizing the LV in all viability images using a ring detector. The detected rings are then aligned with the 3D LV mesh and the SA viability contours are obtained by an affine transformation of this 3D mesh (Figure 5). The resulting contours are positioned with RMS positioning errors of 2.0 ± 0.4 mm and 1.9 ± 0.7 mm, for the LV endocardium and epicardium, respectively [17].

Whole-heart and coronary-artery CMR segmentation

Very recently, a model-based method has been developed for the fully automatic segmentation of all heart chambers and part of the great vessels around the heart [18]. Techniques are also available for the semi-automatic tracking of the coronary arteries in these image data [19]. Figure 6 shows an example of a resulting segmentation.
Overall segmentation performance

Table 1 shows a comparison between the time needed for fully manual segmentation and the time that can currently be obtained with dedicated segmentation algorithms (not including whole-heart and coronary-artery segmentation).

Comprehensive visualization

A widely accepted method of visualizing left-ventricular quantitative analysis results is the “bull’s eye” plot. In this plot, the myocardium is mapped onto a set of concentric rings, where each ring corresponds to one slice of the original image data (Figure 7a). A collection of these bull’s eye plots is used to represent different analysis results, e.g. for myocardial wall thickening, perfusion and viability (Figure 7b). The combined visual interpretation of these plots is left to the clinical user.

A bull’s eye plot does not contain any information about the patient-specific ventricular anatomy. Consequently, it does not show the relation between the left ventricle and other important anatomical structures such as the coronary arteries, the right ventricle and the aorta.

<table>
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<th>Automated (min)</th>
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<td>19</td>
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</tbody>
</table>

Table 1. Time required to delineate a CMR exam manually and with automation.
However, particularly in the case of myocardial ischemia and infarction, it is of the utmost clinical importance to visualize the anatomical relationship between the myocardium and the coronary arteries.

The American Heart Association (AHA) has proposed a standard left-ventricular bull’s eye representation containing 17 segments and has indicated the “standard” relation between these segments and their supplying coronary arteries (Figure 8) [20]. The AHA diagram is a useful guide, but there is a large variation in coronary anatomy. Consequently, the relationships proposed by the AHA are only valid for “standard” patients, so that it is not always possible to uniquely assign a segment to a specific vessel [21].

In order to accurately assess which coronary artery is responsible for the ischemia or infarction, the anatomy of the left-ventricular myocardium and that of the coronary arteries have to be jointly visualized. Moreover, this visualization should also clearly show the regions with reduced myocardial contraction, perfusion and/or viability. In other words, the visualization should be comprehensive, containing all patient-specific anatomical and quantitative information that is relevant for the clinical task at hand.

Figure 9a shows an example of a comprehensive 3D visualization of an automatically segmented whole-heart and coronary anatomy, together with the infarcted regions [22]. The left-ventricular outer surface has been transparently visualized using the surface rendering technique. The inner surface and the surfaces of all other heart components have been visualized in different colors with non-transparent surface rendering.

The infarcted tissue that was semi-automatically segmented from CMR viability images and was registered with the whole-heart CMR image data is represented in yellow using the volume rendering technique. A projection is also made of the 3D ventricle and the coronary arteries on a plane below the ventricle. This projection is in fact a “continuous” bull’s eye plot (i.e. without rings) containing a projected overlay of the coronary arteries.

The visualization in Figure 9a comprehensively shows the relationships between the infarcted myocardial regions and the supplying coronary arteries (arrows). The computer display gives the user the possibility to flexibly rotate, zoom and/or pan the whole-heart visualization and merge it with the original anatomical image data (Figure 9b). Any other quantitative analysis result can be visualized as well, e.g. as a color overlay of the left ventricular outer surface. Furthermore, positional linking is possible between locations on the left-ventricular surface and their corresponding locations in the original anatomical image data.

The whole-heart visualization serves, in fact, as the visual summary of all analysis results and
as the “navigator” for linking to the original image data and associated quantitative analysis results.

**Reporting**

The final step in the analysis chain is the storage and reporting of the results. There is currently no worldwide-accepted storage and reporting format for this data. Generated reports can usually be stored in one or more of the widely accepted formats such as PDF, RFT, MS-Word, HTML, XML, etc.

The DICOM standards committee has recently standardized a template for the structured reporting of 3D CT/MR cardiovascular analysis results: DICOM Structured Reporting (DICOM SR Suppl. 97) [23]. However, this template is only appropriate for a small part of the quantitative analysis results. Segmental analysis results can be included according to the 17-segment AHA diagram, but the template does not contain a standardized representation for the very rich 3D visualizations and associated detailed analysis results that were discussed in the section on Comprehensive Visualization above. DICOM SR does, however, allow the inclusion of information in a proprietary format. Accepting this DICOM SR format would enable at least partially standardized storage of results and operability between analysis and reporting solutions.

**Future research and development**

This article has focused on improving the simplicity of the quantitative analysis of cardiac MR image data. The analysis itself is, however, only one of the links in the chain from imaging to clinical report. There is also a need for Research and Development (R&D) directed towards optimizing the MR imaging itself and optimally coupling imaging and analysis. An example of optimized imaging is auto-viability, a relatively new imaging protocol that automatically provides the optimal contrast between healthy and infarcted myocardial tissue [24].

We have also been mainly concerned with assisting the diagnosis of coronary artery disease. More R&D is needed to extend CMR analysis to treatment planning, follow-up and monitoring, and towards application to other cardiac diseases. For example, CMR analysis may also play an important role in planning the placement of biventricular pacemaker leads for the treatment of atrial fibrillation, and in the diagnosis, treatment and monitoring of congenital heart disease.

Finally, it should be realized that cardiac disease is imaged and analyzed with a plurality of imaging modalities, each having its own characteristics, advantages and disadvantages. Although CMR has the potential to become a “one-stop-shop” diagnostic imaging modality, a combination of imaging modalities will most certainly be applied in clinical practice for the near future. Multi-modality reporting tools will then be needed to optimally combine the complementary information supplied by each of these modalities.

**References**


