Automatic Planning of the Acquisition of Cardiac MR Images

Clare Jackson¹, Matthew Robson², Jane Francis², and J. Alison Noble¹

¹ Dept. of Engineering Science, University of Oxford, UK
`{clare,noble}@robots.ox.ac.uk`

² OCMR, University of Oxford, UK

Abstract. A method to automatically plan acquisition of images aligned with the cardiac axes is presented. The average short axis orientation of images acquired from a group of fifty adult patients is calculated. Localiser images are acquired with this mean orientation. These images are automatically segmented using the Expectation Maximisation (EM) algorithm. The borders of the left and right ventricle blood pools are then found by analysing the properties of the segmented regions. Data points on these borders are used to provide an estimate of the orientation of the cardiac axes.

1 Introduction

Cardiovascular magnetic resonance (CMR) imaging is now regarded as a reference standard for analysis of left ventricular ejection fraction and volume estimation [4]. Correct alignment of the imaging planes with the cardiac planes is very important and a challenge, as previous studies using planes aligned with the axes of the body were shown to be suboptimal [2]. Alignment of the imaging planes with the cardiac axes requires specialist knowledge of cardiac anatomy and many radiologists and technicians find it difficult to plan these images in a time-efficient and reproducible manner [4].

To our knowledge, there has been little research in this area. Lelieveldt et al. proposed a method to automatically orient short axis CMR images using fuzzy implicit surface templates [4] [5]. The work presented here differs from the work done by Lelieveldt in the choice of localiser images and the method used to orient the cardiac axes. Lelieveldt used localiser images which were aligned with the axes of the scanner. However, in this work, the localiser images are already approximately aligned with the short axis of the heart (in a pre-analysis step). Unlike Lelieveldt's localisers, they are breath-hold scans, providing images which give more accurate cardiac positions. Lelieveldt used fuzzy implicit surface templates of all the organs in the thorax to locate the cardiac axes. Our investigations of this method found it to be very computationally intensive, which is a serious problem for rapid feedback to the scanner, so we have not followed that route.

Fig. 1. Example images taken during the usual manual planning procedure

1.1 Manual Planning of Cardiac MR Images

In manual planning, a sequence of localiser and pilot images are acquired which become increasingly closer to the true axis orientations. A typical procedure is described here, based upon the document by Francis [3] which follows Pennell's guidelines for assessing ventricular volume and mass by CMR imaging [6] and the published cardiac imaging standards [1]. This manual planning procedure typically takes a specialist five minutes from the acquisition of the first set of localiser images to the acquisition of correctly aligned short axis images. All the acquisitions are breath-hold at end expiration and end diastole. Example images can be seen in Fig. 1.

Briefly, first a localiser protocol is used to obtain transverse, coronal and sagittal views of the chest (Fig. 1(a)). These images are then used to position vertical long axis (VLA) and horizontal long axis (HLA) pilot images (Fig. 1(b)). The short axis (SA) pilot is positioned using the HLA and VLA pilots. Three slices are acquired with the basal slice parallel to the atrio-ventricular (AV) valve plane. (Fig. 1(c)). The SA pilots are then used to plan the acquisition of HLA and VLA cine images. (Fig. 1(d)). SA images are then positioned using the end-diastolic frames from the VLA and HLA cine images. The first slice is positioned through the AV groove seen on both views. Parallel slices are then acquired until the entire ventricle is covered. (Fig. 1(e)) It should be noted that SA orientation mainly depends upon the position of the AV groove and not on the shape of the left ventricle.

2 Methods

The ideal method for automatic acquisition of CMR images would involve just one localiser sequence. The images from this sequence would be segmented (ideally with no user input) to give left and right ventricle endocardial contours. The SA, HLA and VLA orientations would then be calculated from these contours in three dimensions. These orientations would then be used to acquire correctly aligned images. This is the approach adopted here.

2.1 Localiser Sequence

In this work a multiple slice imaging approach is used with slices oriented with the average SA slice orientation (calculated in Section 2.3). A 3D acquisition was not used as we are presently unable to acquire isotropic voxels of high resolution in the required imaging time. The acquisition is optimised for edge sharpness, high contrast between blood and myocardium and to be compatible with a single breath-hold.

All images are acquired using a 1.5 Tesla Siemens Sonata. A 20 slice acquisition is used with a 280×340 mm field of view, a 1.8×1.8 mm in-plane resolution and a 7.5mm slice thickness with a 7.5mm gap between slices. A “true FISP” sequence is used with a 60° flip angle. The RF reception is on 2 elements of the spine array coil and 6 channels of the anterior phased array coil. ECG gating is used and breath-hold commands are issued via the intercom system. The location of the heart can be estimated with sufficient accuracy to guarantee that this is covered by the slices used.

2.2 Segmentation of Left and Right Ventricle Blood Pools

A Gaussian mixture model is fit to the central (10th) image in the localiser sequence using the Expectation Maximisation (EM) algorithm as described in Ye et al.[7]. We use five Gaussians for the mixture model. The results of applying the EM algorithm can be seen in Fig. 2.

Fig. 2. Segmentation using the EM-MRF algorithm

The pixel values which correspond to the points of overlap between each Gaussian in the model are then calculated. The image is smoothed by replacing each pixel value with the average value of its eight neighbours. Pixels are classified as belonging to one of the five models depending on their value. A set of morphological filtering operations (see Fig. 3) were applied using empirically determined parameters derived from a training set of images. These operations are used to identify the left (LV) and right ventricle (RV) regions.

This process is repeated for all the images in the localiser sequence using the parameters of the Gaussian mixture model found by fitting it to the 10th image. Boundaries of the regions found for a localiser sequence can be seen in Fig. 4. The positions of the centroids of both the left and right ventricle regions are compared to their means over all 20 images. Images where the positions of the centroids are less than one standard deviation from their means are then displayed. The user can then choose to reject images where the regions have not been correctly located.

The normal to the SA is then found by fitting a straight line to the centroids of all the LV regions. The centre of the middle SA slice is set to lie on this line and to be in the middle of the points used for the fit. The SA, VLA and HLA are

Fig. 3. Location of the LV and RV using mathematical morphological operations

Fig. 4. Boundaries of left and right ventricles on all 20 localiser images

set as being at right angles to each other, although, as was discussed in Section 1, this is not necessarily the case when this procedure is performed manually. The centres of the HLA and VLA slices are also defined as being in the same position as the centre of the middle SA slice. This point will be the origin of the heart axes.

The position on the RV boundary which is furthest away from this SA and its angle around the SA vector are then found for each image. The normal to the VLA is defined as passing through the heart axes origin, being perpendicular to the SA and at the average of these angles. The normal to the HLA is then easily found as it is perpendicular to both the SA and the HLA normals.

2.3 Calculation of the Mean SA Orientation:

Recall that in our approach we acquire one localiser sequence with an approximate SA orientation. This is found as follows.

Unit normals to SA images for a group of fifty adult patients selected at random from the data stored on the scanner were used (these were for acquisitions where manual alignment was done). These patients had a variety of heart conditions representative of a cross-section of cases seen in a CMR unit.

The orientations of the axes were converted into spherical polar coordinates. The mean polar angle (angle from the z axis) and mean azimuthal angle (from the x axis in the xy plane) were found and the mean SA normal was taken as a normal vector in the direction given by the two mean angles. The difference in angle between the SA normals and the mean were then found. The mean polar angle was 115° and the mean azimuthal angle was -37° . This can be written as the “Siemens double oblique slice orientation” $S>C37.4>T25.0$. This orientation is a sagittal (S) slice tilted toward coronal (C) by 37.4° and then toward transversal (T) by 25.0° . The average deviation of the axes from this mean is 10.2° . The SA normals and the angle differences are shown in Fig. 5. An illustration of the magnet coordinate system and the directions perpendicular to sagittal, coronal and transversal images can be seen in Fig. 6(a).

Fig. 5. Deviations of SA orientations from the mean SA ($\overline{\text{SA}}$) for 50 patients. (a) shows unit vector normals perpendicular to the SA images, a section of the unit sphere and a plane tangential to this and perpendicular to the $\overline{\text{SA}}$ normal. (b) shows the positions at which the SA vectors would intersect this plane. The coordinates (U,V) represent the distance from the point where the $\overline{\text{SA}}$ normal intersects the plane. Iso-contours show the difference in angle between the SA normals and the $\overline{\text{SA}}$ normal

3 Experimental Evaluation

A patient was positioned with their heart in the centre of the magnet in the z direction. A first set of 20 localiser images was acquired with the calculated mean SA orientation ($\overline{\text{SA}}$) S>C37.4>T25.0 and then a further 8 sets of localiser images were acquired with variations from this mean orientation to simulate different heart positions. The usual manual alignment was then done so the actual HLA, VLA and SA orientations were known for comparison purposes. The angles of the different localiser sequences as shown in Table 1 together with the angles between the calculated orientations, $\overline{\text{SA}}$ and the manually aligned SA, HLA and VLA orientations.

Table 1. Automatic alignment results

Siemens orientation	Angle from axis (degrees)						
	Localisers		Calculated				
	$\overline{\text{SA}}$	SA	$\overline{\text{SA}}$	SA	VLA	HLA	
S>C37.4>T25.0	0.0	9.9	3.9	13.5	17.5	15.1	
T>C-43.4>S27.9	19.5	20.7	12.2	21.9	23.6	17.5	
S>C22.4>T10.0	20.7	22.4	3.1	12.5	23.8	13.0	
C>S37.6>T-10.0	20.7	30.6	4.3	10.3	26.5	11.5	
S>T42.2>C17.0	19.5	10.0	2.9	7.4	24.6	7.6	
C>S37.6>T-25.0	13.6	21.6	12.1	21.1	23.7	14.6	
S>T26.84>C20.0	13.6	8.7	2.1	7.8	25.0	8.3	
T>S43.4>C-27.7	15.0	10.8	6.3	9.6	20.2	8.4	
S>C37.4>T-10.0	15.0	22.9	6.1	15.6	24.2	15.6	

Figure 6 shows (b) the SA orientations of the localisers and the corresponding calculated SA, (c) VLA and (d) HLA orientations. The orientations are displayed as intersections of the normals to the images with three planes in a similar way to Fig. 5. The planes are centred on the mean calculated SA, VLA and HLA orientations and, therefore, show the variability. The average variations of the calculated orientations from their means were 5.6 , 4.6 and 4.2° for the SA, VLA and HLA respectively. (b) illustrates that very similar axes orientations were calculated from all nine sets of localiser images. The angle between the mean calculated SA angle for the 9 cases and the manually aligned SA was 12.8° . This angle was 22.8° for the VLA and 11.9° for the HLA. This shows that the method is reproducible but that the axis orientations, especially that of the VLA, differ from those found manually. Note that our approach has a similar deviation to that of the approach by Lelieveldt [4] which was 12.2° .

Fig. 6. Magnet coordinate system and variation of calculated SA, VLA and HLA

4 Discussion and Further Work

We have developed an approach to automated cardiac axes alignment which uses one localiser sequence and automated image processing. The current approach is semi-automatic and gave results which were reproducible but showed some inconsistencies with the manual approach.

As was described in Section 1, although the manually aligned long axis does align with the long axis of the heart in the mid-plane, it does not align with the axis toward the apex. Similarly, the SA would be expected to be perpendicular to the long axis. This is not always the case as, in the manual approach, there is a tendency to align the SA slice with the AV groove (which may or may not be perpendicular to the long axis as defined previously). There are reasons for all these “tweaks”, which are either historical (e.g. that is the approach that cardiologists use for ultrasound), or due to other analysis steps (i.e. determining the cardiac volume through summing the volumes of multiple slices). Another point is that the VLA is not necessarily perpendicular to the HLA, as might have been expected by those definitions. It highlights that anatomical definitions can differ from computational model definitions. This is discussed in [6]. However, for this application, it appears that a simple computational definition is adequate.

Further work will focus on assessing the significance and relevance of axes that are not mutually orthogonal. The variability of manually aligned axes positions between specialists will also be investigated further. An important next step will be to integrate this planning capability into the running of the MRI system and automate remaining steps which presently require interactivity.

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