Segmentation and Modelling of the Left Ventricle in Human Hearts

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Introduction

The motion of the inside of the left ventricle is of great importance when diagnosing heart diseases. The aim of this project is to create a model that describes the motion of the inside of the left ventricle. The imagery used in this project is magnetic resonance (MR) images provided by Glostrup Hospital obtained from one patient in 2009.

The human heart has 4 chambers: right and left atrium and right and left ventricle. The atria receives the oxygenated (left atrium) and de-oxygenated blood (right atrium). The ventricles pumps the blood to the lungs for oxygenation (right ventricle) and to the rest of the body (left ventricle). Inside the ventricles is a tissue called chordae tendineae or heart strings. These heart strings appears as a part of the muscular wall (septum) surrounding the ventricles on MR-images but should be accounted as part of the inside of the ventricles.

In the first part of this poster we explain the segmentation of a cross section of the left ventricle. In the second part we introduce a model and make it fit the segmented ventricles from the first part.

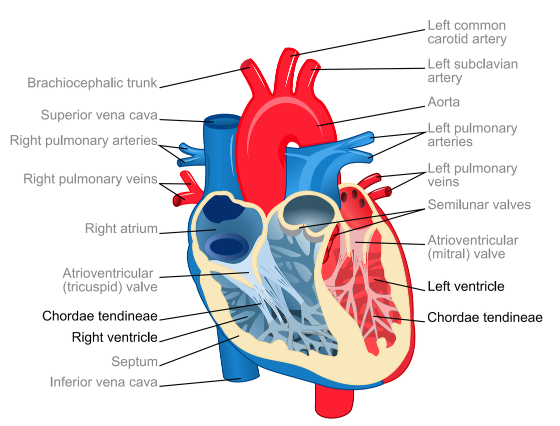
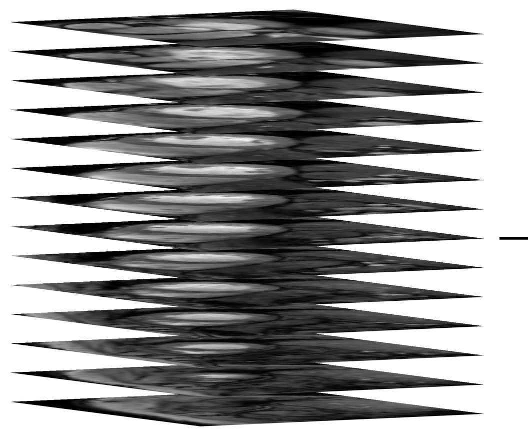


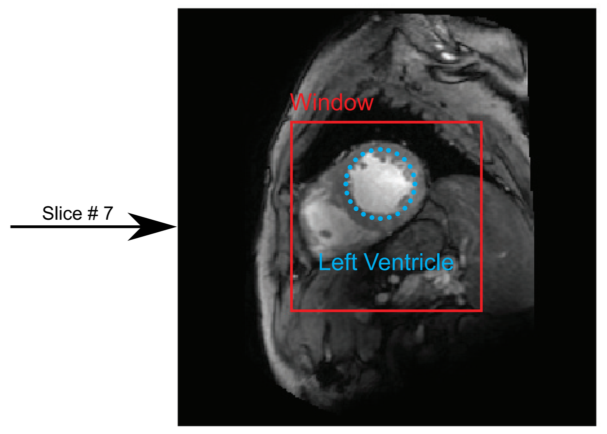
Diagram of the human heart.

Data

The imagery consists of 14 (256x256 pixels) 2D MR-images (slices) through the heart for each of 20 time-frames (frames) hence 280 images. This 4D image material illustrates one heart beat cycle.

We have chosen to analyse on the 7th slice; as the 7th slice holds most information about the motion of the left ventricle. We have removed a 70 pixel boarder of all images because the left ventricle is located near the center in all images.

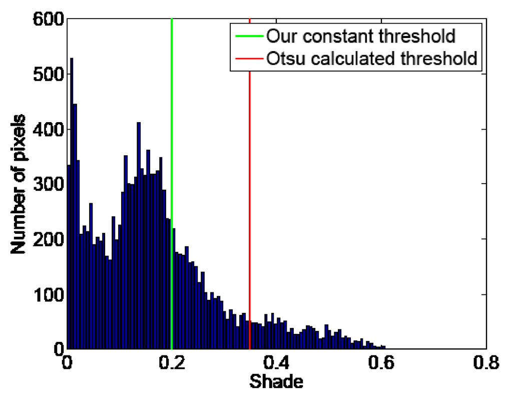




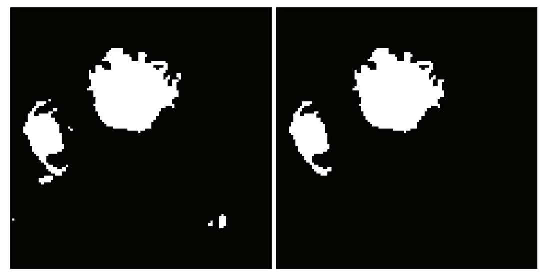
All 14 slices in frame 1 stacked and slice 7 frame 1 with cut-out window and left ventricle marked.

Segmentation

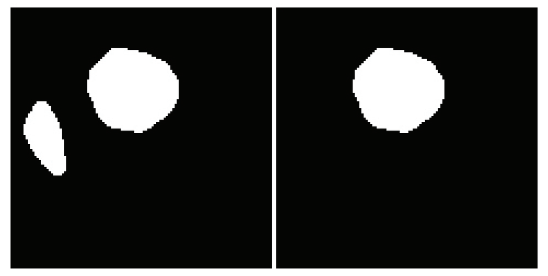
To make a model that describes the motion of the inside of the left ventricle; a sequence of binary images of all frames of the 7th slice is needed. Two methods to create binary images from the MR-images have been used. The following examples only shows the first frame but all operations is carried out on all 20 frames.



The histogram of slice 7 frame 1 with our constant threshold and the optimal threshold.



The binary image calculated on basis of the optimal threshold (left). Objects with a pixel amount smaller than 40 pixels are removed (right).



The histogram of slice 7 frame 1 with our constant threshold and the optimal threshold.

$$R = \frac{4\pi \cdot A}{p^2}$$

The roundness metric formula where A is the area of the convex hull and p is the perimeter of the convexhull.

The first method is described in YingLi Lu et al [1] and follows:

1) The optimal threshold to create a binary image is found as the maximum of the between-class variance of a two class description of the histogram of the pixel values. (The optimal threshold was only applied on pixel values larger than a threshold lower than the desired optimal threshold. This was done to ensure that the optimal threshold was found between the white blood pole and the grey septum.)

2) Remove all objects with a pixel area smaller than a predefined threshold (40 pixels).

3) The convex hull is calculated on all of the remaining areas.

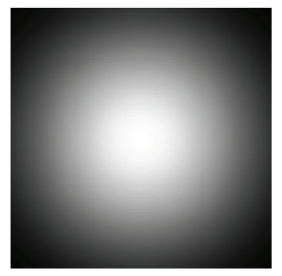
4) The roundness metric is calculated for the remaining objects and the object with the largest roundness metric is used as binary image of the left ventricle.

The second method is our own method and is described in the following:

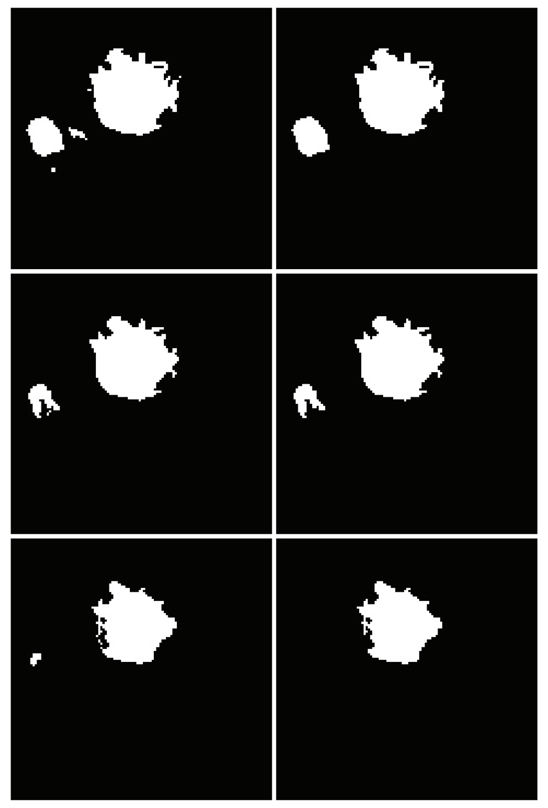
1) A gaussian kernel is applied under the assumption that the left ventricle is placed in the center of the image.

2) The optimal threshold is found from a iterative algorithm leading to only one object. A starting threshold lower than the optimal threshold is used. a) All objects with a pixel area smaller than a predefined threshold (40 pixels) are removed. b) If the number remaining objects are larger than one the threshold is raised and the a) is performed again.

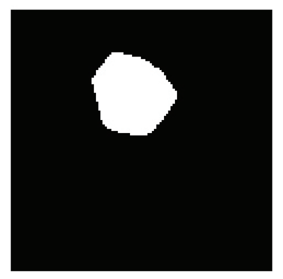
3) When one object is left the convex hull is calculated and used as binary image of the left ventricle.



The gaussian kernel that will be applied on the cut out image. It spans from 1/3 (black) to 1 (white).

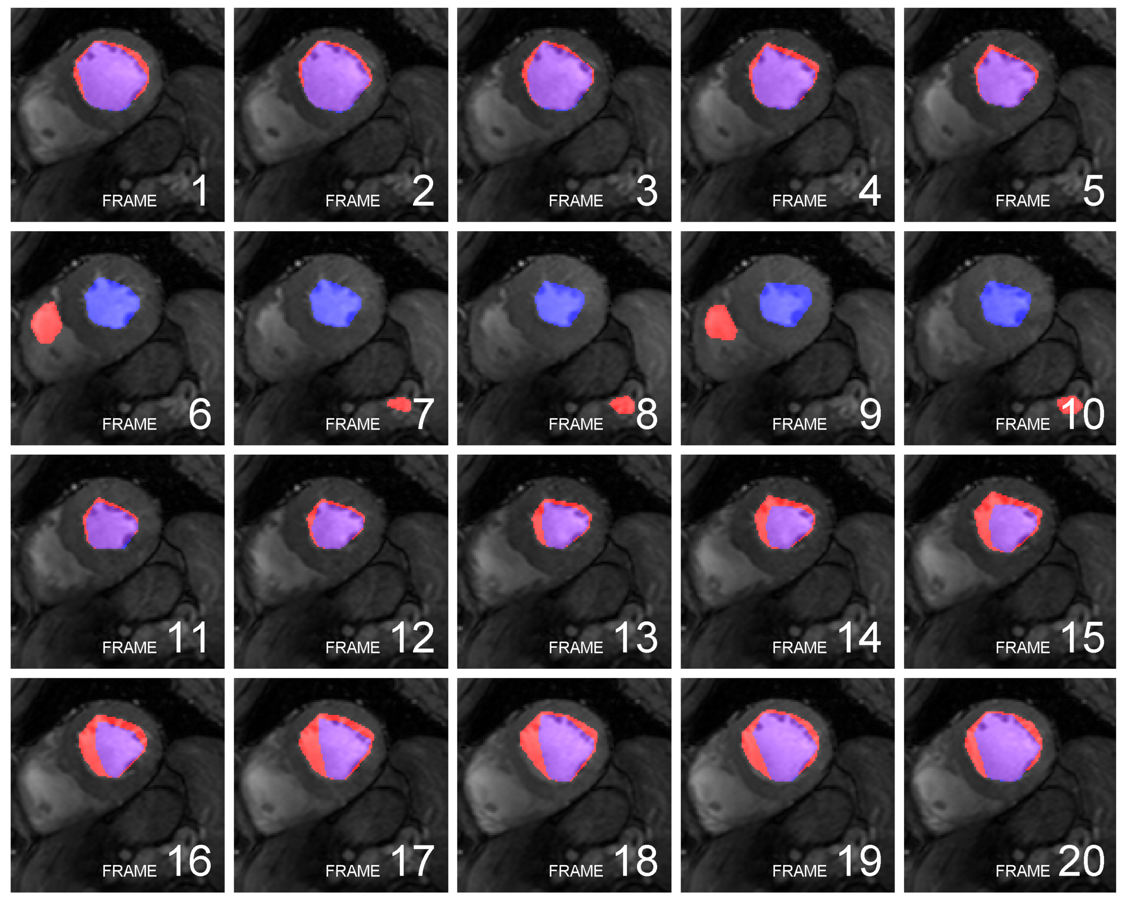


Three iterations vertically. Increasing threshold (left side). Objects with a pixel area smaller than 40 pixels removed (right side).



The convex hull is calculated on the last object.

The two segmentation methods has each its advantages. The Lu-segmentation finds a good left ventricle estimate but can't find the left ventricle in all frames. Our-segmentation estimates the left ventricle a bit too small in the start and end frames but finds the left ventricle in all frames. We use a combination of the two.



The original 20 frames with the binary output image from the Lu-segmentation (red) and our-segmentation (blue) as semitransparent overlay. The overlapped area is purple.

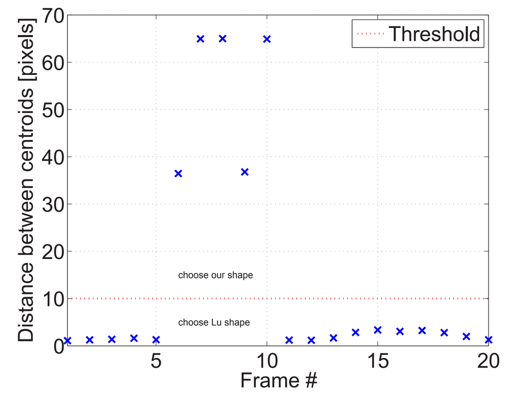
We choose the better of the two methods for each frame by doing the following:

1) Calculating the mass center of the binary image for each frame and method.

2) Calculating the distance between mass centers of the two methods.

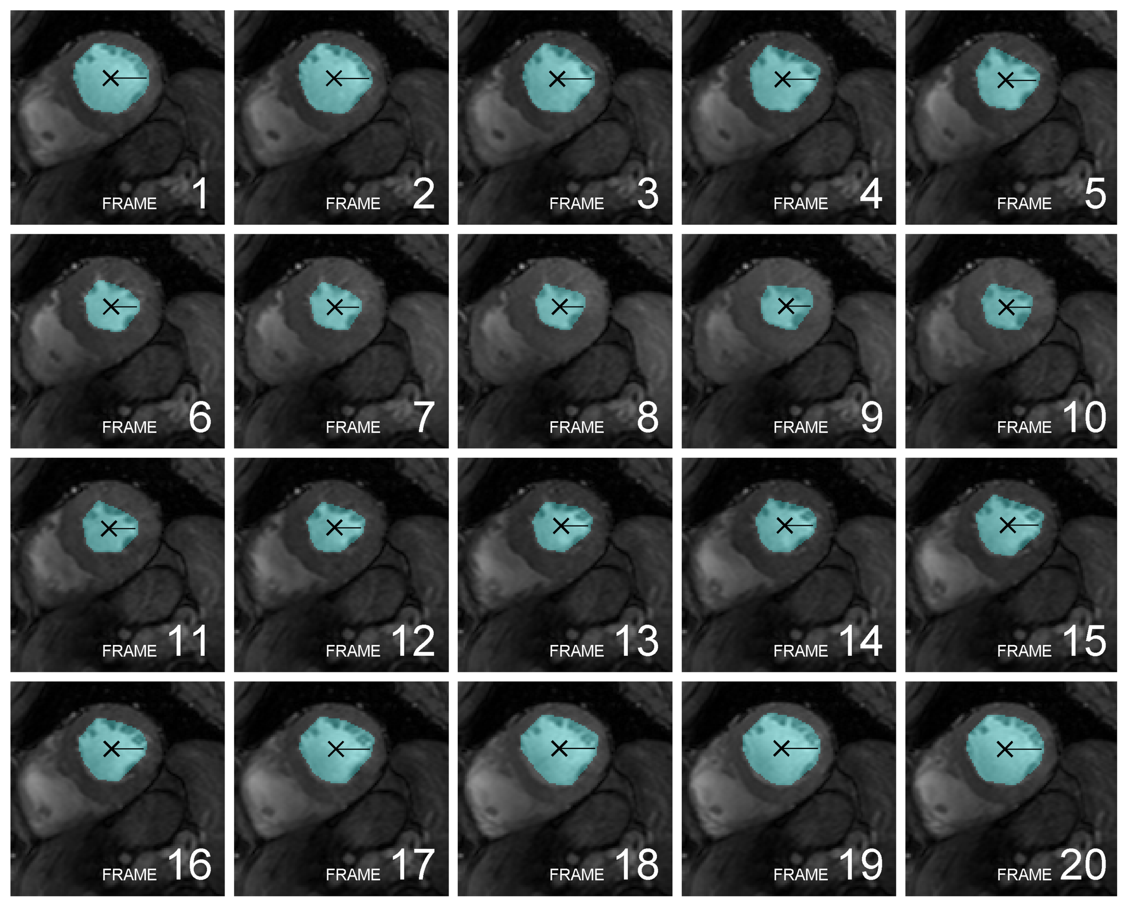
3) Chosing our method instead of the Lu-segmentation when mass centers is farther away than a given threshold (10 pixels).

These 20 best-fitting binary images we call S (segmented images).



Distances between mass centers for the two segmentation methods and threshold.

Modelling



The original 20 frames with the binary image S as semitransparent overlay (cyan) and the mass center (X) and equivalent radius (horizontal line from X).

In this section we introduce a model and make it fit the segmented ventricles.

The equivalent radius of S is calculated for each frame to find tendencies in shape variation used when selecting an appropriate model. The equivalent radius is calculated from the area with the assumption that the shapes is circles.

$$A = \pi \cdot r^2 \Leftrightarrow r = \sqrt{\frac{A}{\pi}}$$

The variation of the equivalent radius is close to a harmonic oscillation (sinusoidal).

The motion of the inside of the left ventricle can be described by concentric circles with harmonic oscillating radii.

To make a better description of the motion of the inside of the wall a model where both the center and the contour of a deformable ellipse can be described by harmonic oscillating functions will be used.

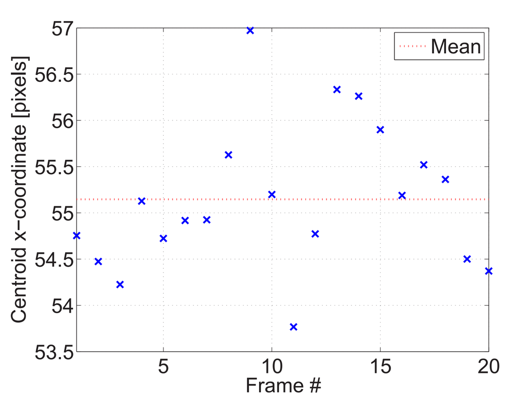
The contour of a deformable ellipse can be described by a 2 by 2 matrix multiplied by a vector describing a circle. Such a model is used in each of the frames.

These six parameters that describes the placement and shape of the ellipses in each of the frames are then coupled by a cosine with a amplitude, phase and DC. The entire model is then described by 18 parameters in total.

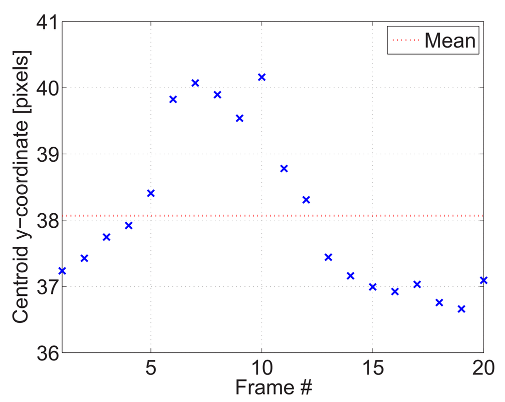
The placement and contour of a deformable ellipse described by six parameters. ▶

$$G = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} r_1 & r_2 \\ r_3 & r_4 \end{bmatrix} \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix}$$

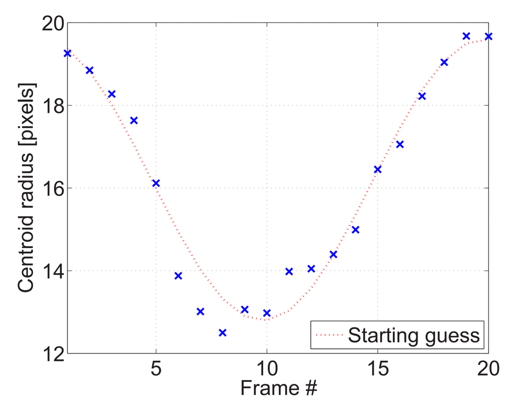
$$\alpha \in [0, 2\pi[$$



Variation of the mass center of S in the x direction. Mean value as initial guess for our model.



Variation of the mass center of S in the y direction. Mean value as initial guess for our model.



Variation of the equivalent radius of S. Sinusoidal as initial guess for our model.

To determine the cost of the placements and shapes of all ellipses, the areas of the ellipses are converted to binary images. This gives a stack of twenty binary images, M.

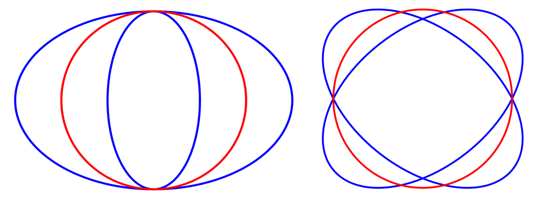
The cost function of the entire model is then simply the sum of the squared pixel-wise differences in each of the two binary images (S and M) for all frames divided by the total number of pixels and the number of frames. To minimize the cost of the placements and shapes of all ellipses the Matlab function fminsearch have been used.

$$H = A_H \cdot \cos\left(2\pi \cdot \frac{\text{frame}_{\#} - 1}{\text{frame}_{\text{TOTAL}}} + \phi_H\right) + B_H$$
$$H = \{x, y, r_1, r_2, r_3, r_4\}$$

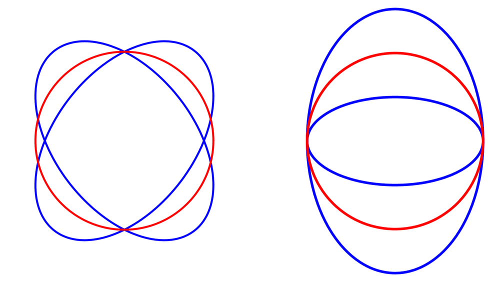
Harmonic function with amplitude, phase and DC for each of the six parameters.

$$F_{cost} = \frac{1}{N_{\text{frames}} \cdot N_{\text{pixels}}} \sum_{f=1}^{N_{\text{frames}}} \left(M_f - S_f\right)^2$$

Cost function used for evaluation in the MatLab function fminsearch.

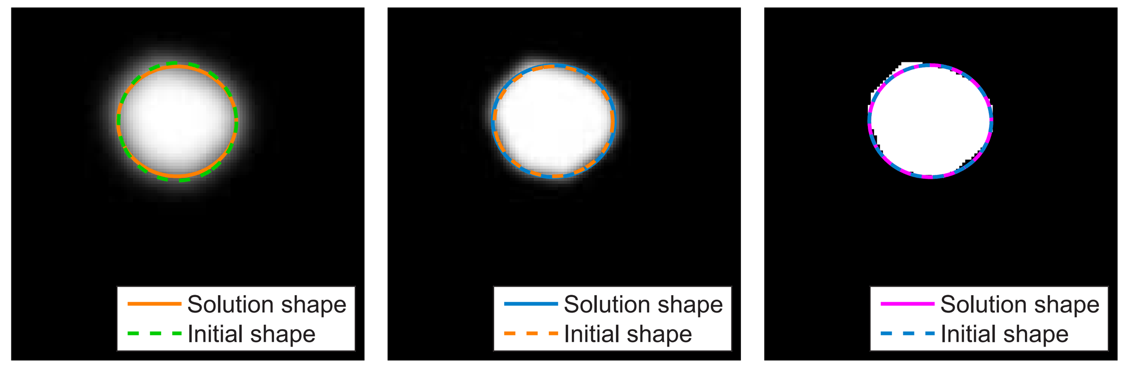


$$\begin{bmatrix} r_1 & r_2 \\ r_3 & r_4 \end{bmatrix} = \begin{bmatrix} 1 \pm 0.5 & 0 \\ 0 & 1 \end{bmatrix} \qquad \begin{bmatrix} r_1 & r_2 \\ r_3 & r_4 \end{bmatrix} = \begin{bmatrix} 1 & \pm 0.5 \\ 0 & 1 \end{bmatrix}$$

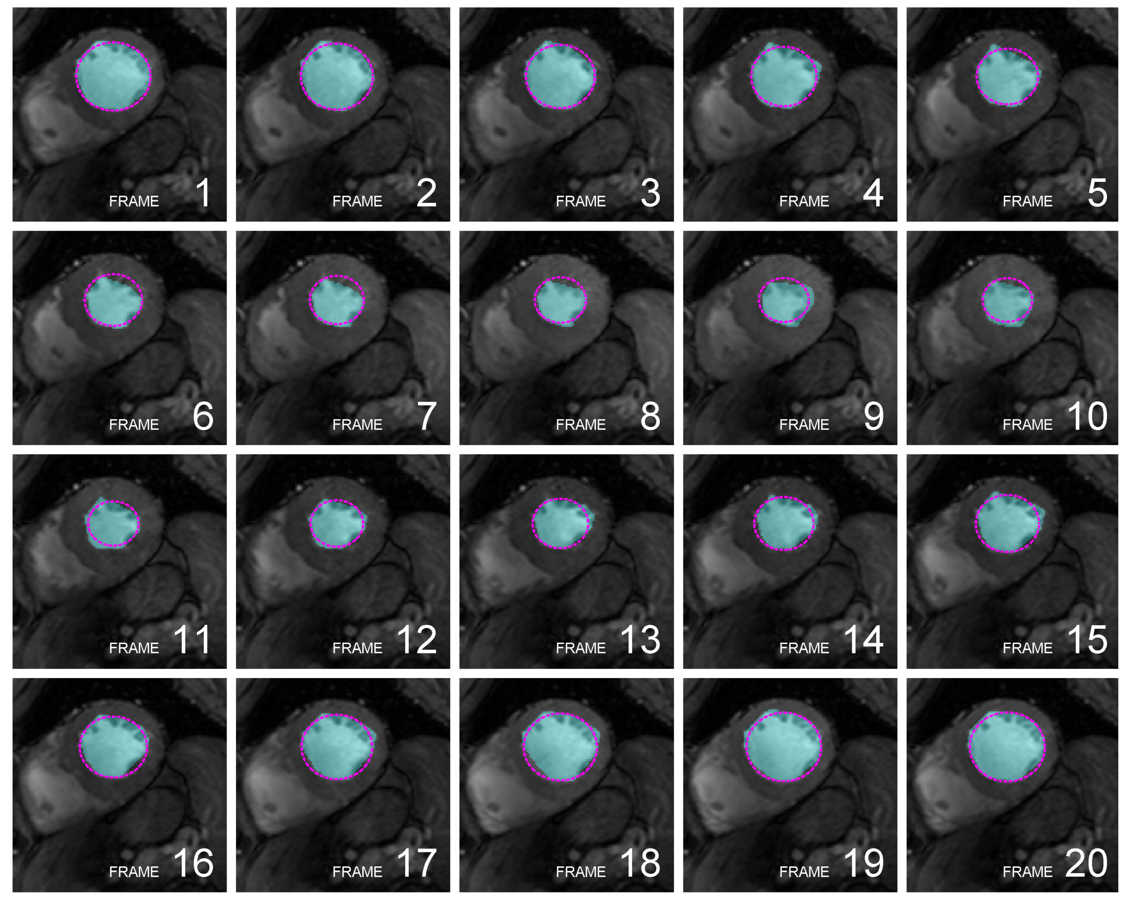


$$\begin{bmatrix} r_1 & r_2 \\ r_3 & r_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \pm 0.5 & 1 \end{bmatrix} \qquad \begin{bmatrix} r_1 & r_2 \\ r_3 & r_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \pm 0.5 \end{bmatrix}$$

The four parameters describing the degrees of freedom of the deformable ellipse.

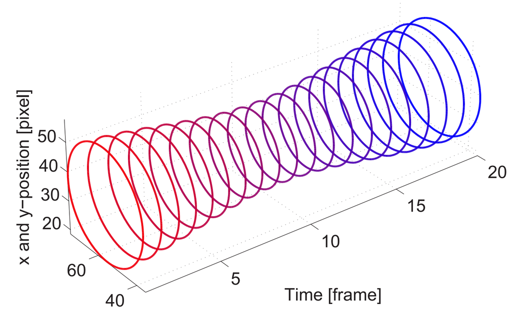


The initial shape and solution shape of three scale spaces of S (1st frame).



The original 20 frames with the binary image S as semitransparent overlay (cyan) and the contours of the final solution shape of the model (magenta).

To ensure the global minimum is found the minimums are found in scale spaces [2] with decreasing standard deviations of S. The solution shape of the first scale space of S is used as initial shape in a scale space of S with a lower standard deviation. This method leads to a final solution shape.



The final solution shape of the model illustrated in each frame.

Conclusions

We get a good segmentation of the left ventricle in all 20 frames by combining our own iterative segmentation method with the one described by YingLi Lu et al [1]. The segmentation includes both the blood pool and heart strings of the left ventricle as it should.

Our 3D model of the motion of the left ventricle during time fits the segmented images so it's possible to see the contraction and retraction of the left ventricle in the model.

Future Work

There is a number of obvious enhancements that could be done on this project in the future. We propose:

More complex model (could be with more harmonics than one and a more deformable shape than an ellipse).

Include the 4th dimension (all slices instead of only the 7th) in the segmentation and model.

Finding the outside of the left ventricle and the right ventricle in the segmentation and include that in the model.

Calculate the model parameters for more patients and find the relation between model parameters and different diagnoses.

[1] YingLi Lu et al. Segmentation of Left Ventricle in Cardiac Cine MRI: An Automatic Image-Driven Method. FIMH 2009 - Fifth International Conference on Functional Imaging and Modeling of the Heart.

[2] Tony Lindeberg. Scale-space: A framework for handling image structures at multiple scales. CERN School of Computing, 1996.