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Mitral Valve Annulus Matching over Time Based on Image Intensities

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Abstract. The mitral valve annulus shape is complex but vital for normal functioning mitral apparatus. In this paper, mitral valve annulus curves at different time instances were matched with image intensities as similarity metric. The quality of matching is described by a cost function, involving a predominant term qualifying the matching quality---image intensities. To ensure the smoothness of the solution to the minimization problem, regularization term was added to generate combined cost functional. Numerical simulation results verified the effectiveness of our method.

Introduction

The mitral valve annulus is a ring-like fibrous entity with a 3D shape resembling a saddle, with the middle portions of the anterior annulus being elevated out of the annular plane towards the left atrium and merging into the aortic mitral curtain. The aortic mitral curtain ends in the left and right fibrous trigone. The annulus contracts and reduces its surface area during systole to help provide complete closure of the leaflets. Annular dilation can result in poor leaflet apposition, leading to mitral regurgitation. The anterior portion of the mitral annulus is attached to the fibrous trigones and is generally more developed than the posterior annulus. The right fibrous trigone is a dense junctional area between the mitral, tricuspid, non-coronary cusp of the aortic annuli and the membranous septum. The left fibrous trigone is situated at the junction of both left fibrous borders of the aortic and the mitral valve[1-3]. The disjunction of the mitral annulus fibrosus could play a role in the development of the pathological features of myxomatous valve disease through the mechanical stress incited by the excessive mobility of the mitral apparatus.

Diagnostic ultrasound employs pulsed, high-frequency sound waves to image tissue structures and their motion. Ultrasound interactions with matter are determined by the acoustic properties of matter. This paper deals with B-mode ultrasound imaging, in which a gray-scale image that represents a spatial map of echo amplitude was presented. In this paper, mitral valve annulus curves at different time instances were matched with image intensities as similarity metric. The quality of matching is described by a cost function, involving a predominant term qualifying the matching quality---image intensities. To ensure the smoothness of the solution to the minimization problem, regularization term was added to generate combined cost functional. Numerical simulation results verified the effectiveness of our method.

Interpolation of Annulus Intensity

Consider a sequence of 3D images indexed by time t. At certain instances, a few number of points were tagged by experienced cardiology experts, which is a meticulous task that cannot generally be replaced by automatic preprocessing algorithms.

Firstly, a continuous version of the discrete image intensity function is needed to acquire the intensity value at any annulus point. Hence, cubic B-splines were applied to interpolate the discrete image to extend it from the pixel grid G to a continuous function of the intensity, as below[4]:

$$J(x)=\sum_{y\in G} b_y B_3(x-y) \tag{1}$$

Where $B_3(x-y)=\prod_{i=1,2,3}\beta(x_i-y_i)$ is the three-dimensional tensor product of one-dimensional cubic B-spline function

$$\beta\ (x)=\beta^0(x)*\beta^0(x)*\beta^0(x) \tag{2}$$

With

$$\beta^0(x)=\begin{cases} 1, & -1/2<x<1/2 \\ 1/2, & |x|=1/2 \\ 0, & otherwise \end{cases} \tag{3}$$

And the set of interpolation coefficients can be computed prior to the computation by solving a linear system. Within the family of polynomial splines, cubic splines tend to be the most popular in applications, perhaps due to their minimum curvature property.

Given m annulus points tagged by experienced physicians, our goal is to interpolate them to get a periodic curve $y=f(t), \forall t\in[1,m]$. For the purpose of periodicity, we extend the m discrete points to both ends by repeating k points, as shown in Fig. 1.

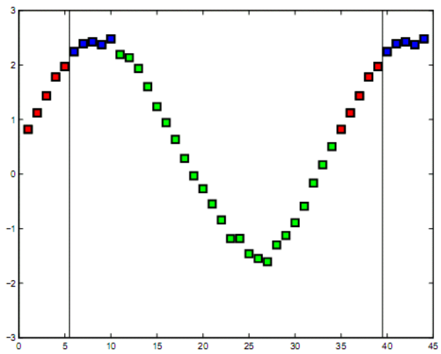

Fig. 1 Extension of annulus points for interpolation

Given points $y_1,\cdots y_n$, the spline interpolation coefficients are computed by solving the following minimization problem:

$$\min_f p\sum_{j=1}^{n}(y_j-f(j))^2+(1-p)\int\left(f''(t)\right)^2 dt \tag{4}$$

The first term is the matching quality to the data, and the second one is the smoothness measure. The cubic smoothing spline

$$f(t)=P(t-j), \quad \forall j\le t\le j+1 \tag{5}$$

And

$$P(x)=c_0^j+c_1^j x+c_2^j x^2+c_3^j x^3 \tag{6}$$

In this way, $f(t)$ has possible jumps, in its value and/or its derivatives, across the interior breaks (1,2,...,n here). Usually in the practical modelization p=0.9 was used, and there is no analytic form for the coefficients $\{c_i^j, i=0,1,2,3; j=1,...,n\}$.

Regularized Cost Functional

We apply the regularization of velocity in the cost function, which can be written as:

$$Cost = Match + \lambda * Reg \tag{7}$$

Where the matching error

$$Match = \sum_s (J_2(\phi(s) - J_1(s))^2 \tag{8}$$

$\phi(x) = \int_0^x v(s)ds$ is the deformation function, J_1, J_2 are the intensity quantiles of reference and target annulus. And the regularization is the variance of the discrete velocity

$$v(x) = a_i, \quad \forall x \in \left(\frac{i-1}{n}, \frac{i}{n}\right] \tag{9}$$

i.e.,

$$Reg = Var(a) \tag{10}$$

Numerical Evaluation

Echocardiographic images were acquired with 3D transesophageal echocardiography. The Cartesian data were uploaded to an interactive mitral valve modeling program developed by our group. For each selected instance, 36 points along the annulus were tagged and exported to a Matlab environment to generate a continuous annulus curve. Fig. 2 illustrates the simulation results of our algorithm between two annuluses, in which we use n=10 intervals for velocity discretization, 200 iterations in the gradient descent optimization, from which it can be observed that after matching the intensities between reference and deformed target annulus curves matched quite well.

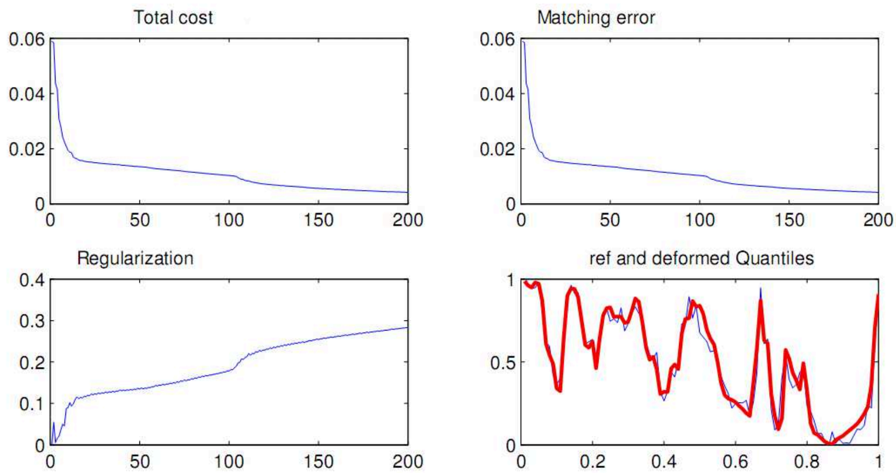

Fig.2 Computation results

Summary

The disjunction of the mitral annulus fibrosus could play a role in the development of the pathological features of myxomatous valve disease through the mechanical stress incited by the excessive mobility of the mitral apparatus. This paper deals with B-mode ultrasound imaging, in which a gray-scale image that represents a spatial map of echo amplitude was presented. This paper proposed an algorithm to match mitral valve annulus curves at different time instances based on image intensities.

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