# Cardiac deformation mechanics from 4D images

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An approach is presented for analysing cardiac deformation mechanics. A physics-based deformable model is trained from a set of 4D images. The mechanics of myocardium are quantitatively analysed and the working conditions of the heart are statistically evaluated by observing their deviations from normal values.

*Introduction:* The research to diagnose and prevent cardiovascular diseases becomes more important than ever [1]. Estimating the global functions of the heart accurately, and in a clinically useful way, is a very important yet an open research problem. Over the past decade, there have been a great deal of model-based approaches to the analysis of the complicated motion of the heart [2, 3]. The limitation of such traditional techniques is that they do not provide intuitive motion parameters to describe the non-rigid motion of the heart. Recently, some attempts have been made to characterise the cardiac mechanics with finite-element methods and mostly the functional analyses are related to wall motion and wall stress for identification of myocardial infarction. For example, Wu *et al.* discuss the wall motion with infarction in magnetic resonance images (MRIs) [4]. Ledesma-Carbayo *et al.* contribute strain analysis on the left ventricle (LV) [5]. One main problem still existing, however, is that people often relate dynamical parameters directly to some cardiac problems without considering locational effect and individual difference. The heart is in fact a complex system and conditions may be very differently distributed. For this reason, functional evaluation in this research is applied locally and with statistical knowledge. Furthermore, this research concerns not a single motion parameter, but a set of combined dynamical factors.

*Method:* Based on the model-driven techniques for cardiac imaging interpretation developed in the past few years [6], this research proposes a content adaptive object modelling (CAOM) method to capture the general shape of a heart, as well as its shape variation, object neighbourhood information, and object boundary structure of the anatomical view from the image volumes. The method is statistically based and very suitable for medical image interpretation and deformation analysis. In general, the method works in two stages. The first is the training stage, which includes sample set collection, accurate shape description, discrete representation, geometrical transformation, statistical processing to learn shape variation, and creation of the generalised cardiac model. In this research, the statistical model of the cardiac shape is created from about 200 cases in three hospitals.

The second stage is instance interpretation. When a series of images of a new case are read to the system, it first needs to properly locate in the image volume and fit the shape according to the actual content around the object after active segmentation [7]. The CAOM comprises a generalised object shape and statistical appearance in the image environment. The former primarily holds information about the cardiac shape while it allows variation in a statistical model. The latter is responsible for learning content patterns from the training datasets. In this research, we are concerned mostly with the left ventricle, represented by about 1000 3D points. The cardiac CAOM is expressed as $\omega = \varpi + \Phi b$, where $\omega$ is an instance of cardiac shape, which is a vector containing the 3D surface points, $\varpi$ is the normalised mean shape of the heart, which should be constructed during the training stage, $\Phi$ is a matrix containing some principal eigenvectors and each vector represents the direction of shape variation, and $b$ is a vector of actual variation of an instance from the trained model.

With the statistically constructed CAOM, a set of regional points of interest in a new case can be tracked accordingly. Some important parameters of regional cardiac dynamics analysed in this study are: the positional displacement, velocity, acceleration, force, stress and strain. These parameters are the basis of cardiac tissue motion and can help physicians to analyse the cardiac status. Before computing these parameters, a set of points of interest are assigned for tracking in the 4D image sequence. Without special clinical reason, often tens or hundreds of points are automatically selected from all areas of the cardiac surface so that the whole heart can be evaluated.

A myocardial tissue is tracked by CAOM fitting and interpretation so that it knows where a point comes from in the last phase and where it goes in the next phase. To measure the deformation in the myocardium, we may start with an estimation of voxel displacement. Consider a number of phasic shapes constructed in one cardiac cycle. Each phase is sampled by a fixed frequency (e.g. 100 ms per frame). Practically, a 4D cardiac image set is represented as $I = f(x, y, z, t)$, where a point in the sequence is $M = (x, y, z, t)$. The radial displacements on the ventricular myocardium are obtained by using the tissue-tracking algorithm in CAOM. For a point $M_1$ at time $t_1$, which is mapped to a point $M_2$ in the deformed myocardium at time $t_2$, the radial displacement is then $d = \boldsymbol{u}_1 \cdot (M_2 - M_1)$, where $\boldsymbol{u}_1$ is the unit radial vector at $M_1$. Here we have assumed $\Delta t = (t_2 - t_1) \to 0$. The excursion is defined the maximum radial displacement and is importantly measured in this study.

The radial velocity of a voxel is $\boldsymbol{v}_1 = d\boldsymbol{u}_1/(t_2 - t_1)$ and its external force is $F_1 = \rho_m \Delta_V\ (\boldsymbol{v}_2 - \boldsymbol{v}_1)/(t_2 - t_1)$, where $\rho_m$ is the density of cardiac muscle and $\Delta_V$ is the volume size of the voxel at $M_1$. To analyse the wall stress, Laplace's law can be applicable to differential areas of the cardiac 3D shell under a pressure load. The general representation of wall stress is $\varsigma = PR/(2h)$, where $P$ is the pressure applied on the voxel, $R$ is the curvature radius at $M_1$, which can be approximated as the distance from the origin of the bisectors to their intersection on the short-axis view of the ventricle, and $h$ is the thickness of the shell, which is also measured along the radial direction. The wall stress is thus inversely proportional to the wall thickness $h$ in a differential segment. The final determinant of wall stress with the use of a Laplace's law formulation is cavity pressure. The radial component of the wall stress is $\varsigma_r = \varsigma \sin(\Delta_\theta/2)$ where $\Delta_\theta$ is the sphere angle of the voxel.

The myocardial strain can be calculated from the dense displacement field using a Green-Lagrange strain tensor [5]. For the 4D image, we first compute the deformation gradient tensor: $\boldsymbol{D} = [\partial \boldsymbol{g}_i/\partial x,\ \partial \boldsymbol{g}_i/\partial y,\ \partial \boldsymbol{g}_i/\partial z] + \boldsymbol{I}$, where $\boldsymbol{I}$ is an identity matrix and $g_i$ is the dense displacement field computed from the image $f$ along the three directions. Finally the strain tensor is $\boldsymbol{S} = (\boldsymbol{D}^T\boldsymbol{D} - \boldsymbol{I})/2$. So far we can compute the displacement, velocity, force, stress and strain in a 4D cardiac image.

Previously researchers attempted to use one or two of these parameters directly to judge some cardiac motion problems. It is, however, very difficult to tell the quantities truly related to abnormality or not since all these parameters vary very much from different areas of the heart. It is important to use statistical strategies for evaluation of the cardiac functions. This research marks nearly 1000 featured points on the cardiac shape among which a large part are set on the left ventricle (Fig. 1*a*). Each of them is statistically modelled. Information learned from the training set during CAOM construction includes its relative position on the heart, its mean values and derivations of excursion, velocity, force, stress, strain, etc. Normally these parameters should be in Gaussian distribution.

The evaluation is carried out to compare some specific parameters with those in the learned database. For example, with the 4D cardiac image of a new case, a few important points on the cardiac shape are selected to compute its properties of dynamics. If the value is relatively far outside the mean, it is known of low activity of the myocardium around its area. Especially, the value below two standard deviations is recognised as 'very inactive' and the value below three standard deviations is recognised as 'abnormally inactive'.

*Results:* This research investigated a series of 4D images for cardiac evaluation. Hundreds of points are assigned on the cardiac surface to observe the myocardial deformation mechanics. It is informative to identify the cardiac deformation quantitatively in vision. Experiments demonstrated the applicability of the above technique by illustrating the dynamical parameters described above. Fig. 1*b* shows some marked points on the cardiac surface for dynamic tracking. Fig. 2 quantitatively visualises some important dynamic parameters for a specific point or the distribution on a ventricle. The diagnosis of ventricular defects can be made on the standard deviations from the statistical distribution of the training set. The defect area and location can be illustrated visually for further clinical decision and medical treatment.

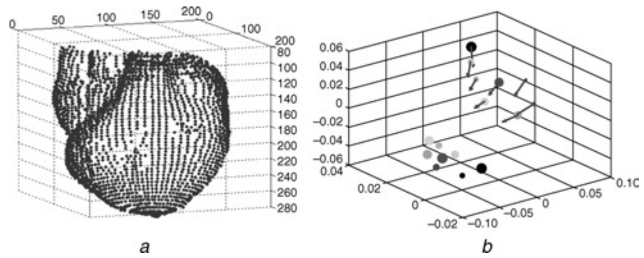

**Fig. 1** *(a) Number of points distributed on cardiac shape for statistical analysis of dynamical functions. Each point is modelled with its relative position and statistical values of all dynamical parameters; and (b) A few regional tracked points for evaluation of cardiac deformation mechanics. Displacement, velocity, acceleration, force, and stress are derived from 4D image sequence with tissue tracking method*

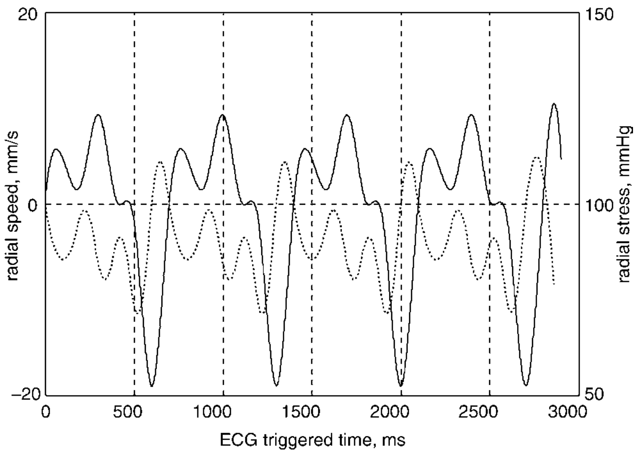


**Fig. 2** *Analysis of correlated radial velocity and myocardial strain in cardiac periods*

In our practical study, a table of all tracked points is constructed to analyse their dynamics and warn on some abnormal points with corresponding spatial positions. Table 1 gives the evaluation result of a few points around the left ventricle, where we can know the regional maximum velocity, force, strain, and excursion of myocardium through the cardiac cycle. The 'not so active' areas are labelled with '-' or '- -', according to the extent of their deviations from normal values.

**Table 1:** Example results of automatic highlighting for abnormal mechanics

| Tracked point | Velocity | Force | Strain | Displacement |
|---|---|---|---|---|
| Inf1 | - | ○ | + | - |
| Lateral1 | ○ | - | ○ | ○ |
| Ant1 | - - | - | - | - |
| Ant2 | - | - | ○ | - |
| Septum1 | ○ | ○ | ○ | ○ |

○ tissue mechanics in normal range (within 67% of the statistical population), - inactive and below 1-sigma, - - very inactive and below two-sigma
+ active and beyond 1-sigma

*Conclusions:* Important dynamic parameters based on a statistical model have been analysed. In the special physics-based deformable model used in the study, regional structure and statistical dynamics are available for cardiac shape fitting and ventricular defect evaluation from the 4D image. Visualised regional mechanics and labelled defective status will help us to estimate the working conditions of the heart and find possible cardiovascular diseases even in the early stage.


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