Computer Simulation of the Left Ventricle Contraction

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ABSTRACT

Method of computer simulation can best be done for the construction of quantitative characteristics of LV contraction. This method make it possible to perform quantitative assessments of one or the other pahtology of the LV operation as well as one or the other construction of artificial aortic valve in advance. The main difficulties of computer simulation are the complicated shape of LV (Fig. 1) and the complicated form of LV contraction. In this regard to describe LV contraction the 61 characteristic points of the three-dimensional image of LV were chosen. The position of these points during LV contraction was determined using the "capture method". The positions of other points were determined by means of spatial interpolation. The algorithm for controlling the LV mechanical model in three axes: longitudinal, transverse and twisting was proposed.

Keywords

Computer simulation, left ventricle, spatial interpolation, LV model, control process

1. INTRODUCTION

The operation of the LV in large measure is responsible for the circulation of the blood. That is why this process is the subject of the investigation for different researchers.

In the greater part of previous studies for the simulation of the LV contraction the authors used the simple geometric surfaces, such as a sphere [1], cylinder [2] and ellipsoid [3, 4]. However, firstly, LV has a more complex shape (Fig. 1) and when contracted, it not only shortens and it shrinks in
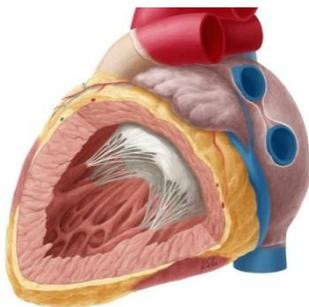

Fig. 1. The longitudinal section of left ventricle.

across, but also twists. Secondly, the compression of the above figures reduces the diameter of the outlet and third, the ejection function in these models is generally not described. In addition, attempts to calculate stresses in the walls of the LV by placing muscle fibers over such simple surfaces lead to incorrect results.

More realistic is the model based on the longitudinal and transverse contours of LV on echocardiograms (Fig. 2) obtained at the beginning and at the end of the contraction [5]. In addition, this model is constructed in such a way that the blood flow at the LV output corresponds to the experimental one (Fig. 3).

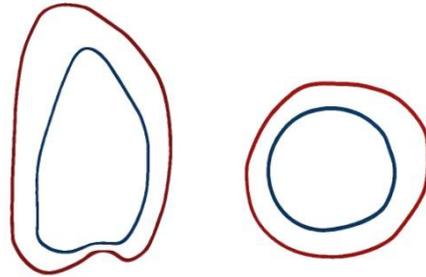However, this model does not reproduce the effect of twisting.

Fig. 2. Longitudinal and transverse contours of LV obtained at the beginning and at the end of the contraction.

At the same time the spatial form of LV obtained by computer tomography [6] and magnetic resonance imaging (MRI) [7, 8] is more accurate. On the one hand this last-mentioned method is more informative for the diagnostics due to clearer images (static and dynamic) and the ability to make more accurate measurements.
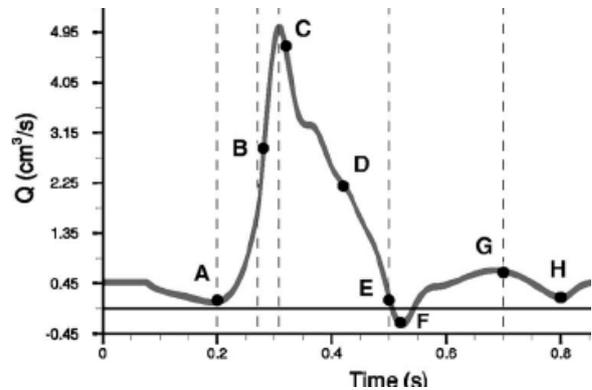

Fig. 3. The blood flaw at the LV output during a systole.

But on the other hand, mathematical modeling of LV contraction based on MRI leads to the need to operate with huge arrays of numbers representing a three-dimensional image of LV. Even with voxel representation of the LV surface will need from 6 to 10 thousand numerical values in each of the successive time moments of MRI investigation.

2. COMPUTER SIMULATION OF LV CONTRACTION

2.1. Moving of model frame

To avoid this difficulty, it was decided to choose the characteristic points of the three-dimensional image of LV, representing the moving surface of LV in the best way. In our case the number of these points was equal to 61 (Fig. 4). Using the capture technology for the selected points, it is possible to determine their positions at any time during systolic contraction. This can be considered as computer

simulation of the moving frame of the LV mechanical model. In order to simulate the motion of any point of the LV surface, the spatial interpolation method can be applied.
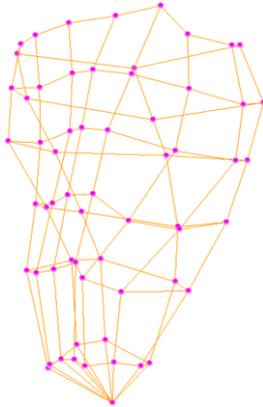

Fig. 4. 61characteristic points of the LV surface.

2.2. Three-cubic interpolation

In this paper we used the method of the local three-cubic Hermite interpolation, which is a way for obtaining the values of arbitrary points in the 3D space of a function defined on any grid. The interpolation program was written in C++ using modules and CMgui API. Coordinates of nodes and values of derivatives in these nodes were entered as input data. The result of the computer program is shown in Fig. 5, *a*) – in the beginning and *b*) – at the end of contraction.
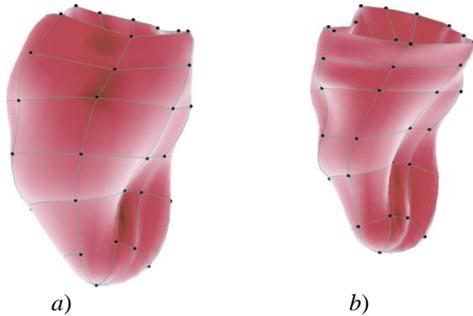

a)   *b*)

Fig. 5. The model of the LV surface in the beginning *a*) and at the end of contraction *b*).

2.3. Control of LV model

In the previous section, it was shown how the proposed model reproduces the form of LV at various points of its reduction. This section proposes a method of model control in the contraction process. It is based on subdivision of the model into several (six, for example) transverse layers (Fig.6). For the structure obtained in this way, it is proposed to perform three operations: longitudinal compression, transverse compression and rotation of each layer. The first operation is simple enough and is coming to reducing the thickness of each layer. The second operation consists of contraction of each layer, but not necessarily uniform in direction. The third operation is the most complex because it consists in rotation of each layer, but the centers of rotation of the layers do not necessarily lie on the same straight line. In the simplest case, when the twist occurs around straight longitudinal axis, it is possible to record the coordinates of any point on the LV model surface in a cylindrical coordinate system (r, z, t) and any time t in the following way:
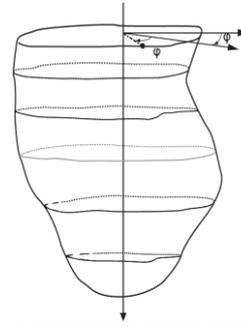
$$r = f(z, \varphi, t)$$

Fig. 6. Subdivision of the model into six transverse layers

In this case we can record the above operations for each layer with number i:
1) longitudinal compression: $z_i = z_{0i}\omega(t)$;
2) transverse contraction: $r_i(z_i, \varphi, t) = R_0(z_i, \varphi)T(z_i, t)$;
3) rotation: $\varphi(t, z_i)$.
The functions $\omega(t)$, $T(z_i, t)$ and $\varphi(t, z_i)$ can be considered as control functions for each layer. As an example, below (Fig.7) are the graphs of $T(z_i, t)$ for six sections.
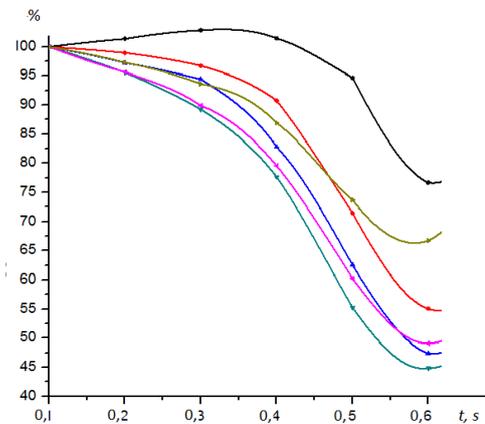

Fig. 7. Graphs of $T(z_i, t)$ for six sections

REFERENCES

[1] K. Campbell, A. Simpson, S. Campbell. "Dynamic left ventricular elastance: a model for integrating cardiac muscle contraction into ventricular pressure-volume relationships" *J. Appl. Physiol. 104*, pp. 958-975, 2008.
[2] R. S. Chadwick "Mechanics of the left ventricle" *J. Biophys. 39*, pp.279-288, 1982.
[3] R. C. P. Kerckhoffs, O. P. Faris, P. H. M. Bovendeerd, F. W. Prinzen, K. Smits, E.R. McVeigh, T. Arts "Electromechanics of paced left ventricle simulated by straightforward mathematical model: comparison with experiments" *J. Physiol.: Heart Circul. Physiol. 289*, pp.1889-1897, 2005.
[4] V. Rolle, C.Guy , R. Pierre-Yves, P. Pibarot, D. Louis-Gilles, A. A. Hernandez. "A tissue-level electromechanical model of the left ventricle: application to the analysis of intraventricular pressure" *J. Acta Biotheoretica. 57*, pp. 457-478, 2009.
[5] A. Radichkina, V. Tregubov. "Mathematical simulation of the left ventricle during the systole contraction". *Int. Conf. of the Polish Society of Biomech. Book of abstr.*, pp. 185-186, 2010.
[6] M.Perl, A. Horowitz, S. Sideman. "Comprehensive model for the simulation of left ventricle mechanics" *J. Med.Biol.Eng.Comput. 24*, pp.145-149, 1986.
[7] F. Dorri, P. F. Niederer, P. P. Lunkenheimer. "A finite element model of the human left ventricular systole" *J. Comp. Methods in Biomech. and Biomed. Eng., 9 (5)*, pp. 319-341, 2006.