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Quantitative Assessment of Intraventricular Flow State Using Tornado-Approach to Hemodynamic Analysis

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Abstract **–**Previously, it was shown that blood flow in the heart and major arteries refers to a class of self-organized tornado-like flows of viscous fluids, which can be quantified by means of special exact solutions of nonstationary hydrodynamic equations. Exact solutions allow us to establish the relationship between the dynamic anatomy of the left ventricle and the hydrodynamic structure of the tornado-like blood flow. The extent of the flow nonsnationarity is characterized by a time-dependent functions contained in the exact solutions which correspond to the radial velocity gradient and the circulation of tornado-like jet. The ratio of these functions is proportional to the ratio of potential (longitudinal and radial) and dissipative (azimuthal) velocity components. The dynamic volume of Tornado-like jet in the cavity is proportional to parameter Q, calculated from the exact solution and dependent on geometrical configuration of the cavity. The both parameters can be measured in the MSCT images of left ventricle. It was shown that these criteria accurately reflect the evolution of the flow in normal and hypertrophic cardiomyopathy hearts, indicating the degree of flow swirling in the cavity of the left ventricle and the effectiveness of cardiac output.

Keywords**:** Tornado-like flow, blood flow in the left ventricle, quantitative analysis of intracardiac blood flow

1. Introduction

Modern instrumental methods of visualization and measurement of blood flow have shown that the flow in the transport segment of circulation has a twisted structure. However, quantitative analysis of this stream is difficult due to lack of adequate simulation model with which it would be possible to describe the structure of the flow, i.e. the velocity and pressure fields in the blood stream. This is necessary for the understanding of the mechanisms of formation and evolution of cardiac jet and for the structure and efficiency of diagnosis of cardiac output. Whereas it is necessary for the understanding of the mechanisms of cardiac jet formation and evolution, and for the correct diagnostics of the flow structure and efficiency of cardiac output.

The studies performed at the Kurchatov Institute of Atomic Energy at the end of the 70s, had resulted in the find of a special exact solutions of the Navier-Stokes and continuity equations for a class of self-organizing tornado-like flow (Kiknadze G.I., Krasnov Y.C., 1986). This solution describes the velocity field of the viscous flow corresponding to natural tornadoes in cylindrical coordinates (1):

$$
\begin{cases}
V_r = -C_0(t)r \\
V_z = 2C_0(t)z \\
V_\varphi = \frac{\Gamma_0(t)}{2\pi r}\left(1 - e^{-\frac{C_0(t)r^2}{2\nu}}\right)
\end{cases}
\qquad (1)
$$

where V_z is longitudinal, V_r is radial, and V_φ is azimuthal velocity components, C_0 is a radial velocity gradient [sec^{-1}], Γ_0 is circulation of jet [m^2/sec]; $C_0(t)$, $\Gamma_0(t)$ – arbitrary time-dependent functions, changing due to the flow nonstationarity, ν – kinematic viscosity [m^2/sec].

Previously we have shown that the geometric configuration of the flow channel of the heart and aorta corresponds with high accuracy to the directions of the current lines of Tornado-like flows (Gorodkov A., et al. 1996). So we have used the exact solutions for the development of new quantitative criteria that reflect the dynamics of the tornado-like jet generation and evolution in the heart. To validate the approach we have studied how the pathological changes in the geometric characteristics of the left ventricular cavity in the hypertrophic cardiomyopathy patients affects the properties of cardiac jet and what are the possible mechanisms to reduce the effectiveness of cardiac output.

2. Materials and Methods

10 patients were examined, 5 of whom had no marked changes of geometrical relationships in the cavity of the left ventricle, and 5 patients were diagnosed with severe hypertrophic cardiomyopathy (HCM) after comprehensive survey conducted in the Bakulev Research Center of Cardiovascular Surgery.

Patients have passed the standard examination using contrast multislice computed tomography. There were obtained The three-dimensional images of the left ventricular cavity corresponding to ten time moments during the cardiac cycle were obtained. These images were analyzed using the software package Blender. The elements of trabecular profile on the surface of the cavity were identified, which preferential direction coincided with the diastolic and systolic blood movement, as it has been shown in previous studies (Bockeria L.A., et al., 2013). The position of the straight axis of the inlet and outlet tornado-like flow portion was calculated so that the radius of the channel, and the trabeculae inclination along the flow always decreased with increasing of the longitudinal coordinate values, and the tilt angles of the trabeculae to the axis were equal at the same value of the longitudinal coordinate. The position of the axis of the inlet part of the left ventricle was calculated in the diastolic images of the cavity, and the axis of outlet flow was calculated in the systolic images (Fig. 1).

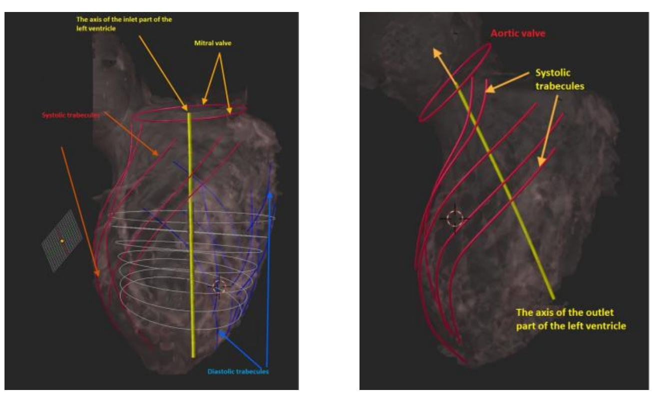

Fig. 1. Position of the axes of input (left) and output (right) left ventricular flows in reference with preferential directions of intracardiac trabecules using the MSCT images.

The values of the structural parameters of intracardiac blood flow - the ratio of the radial velocity gradient to the circulation flow (C_0/Γ_0), and the volumetric jet parameter (Q) were calculated by the formulas given in (Bockeria L.A., et al., 2013).

The data obtained were processed statistically; the degree of reliability was assessed by Pearson.

3. Results

For all patients the characteristic plots $C_0/\Gamma_0(Q)$ and Q(Z) corresponded to the first-order hyperbola, and to the linear function, respectively (Fig. 2). This justified the plotting of dynamic dependences of these parameters on the time since all the measured values belong to the structure of the tornado-like flow in the left ventricular cavity (Fig. 3).

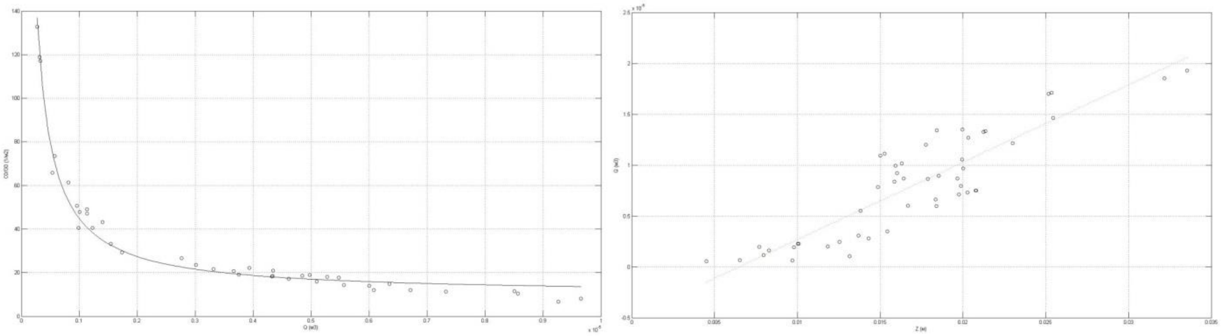

Fig. 2. Characteristic dependences $C_0/\Gamma_0(Q)$ (left) and Q(Z) (right) showing that all measured values C_0/Γ_0 and Q belong to the Tornado-like jet.

The phase structure of the dependence $C_0/\Gamma_0(T)$ in normal patients corresponded to that, previously described in (). The jet was swirled in inlet part of the left ventricle, accumulated kinetic energy that was spent for the acceleration of the jet during the ejection in the aorta. The ratio of potential and dissipative velocity components decreased since the opening of the mitral valve as jet acquires twisting due to diastolic trabecules, and then increased as soon as the jet purchase radial impact by contraction of the left ventricular wall. The volume of intracardiac jet increased relatively slowly during diastolic filling, and decreased at a higher rate to eject the blood into the aorta.

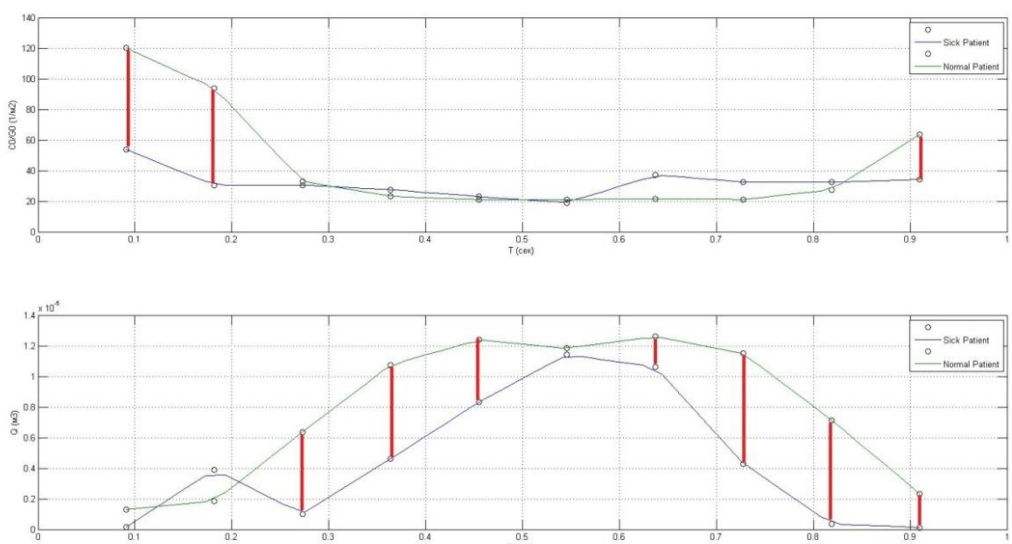

Fig. 3. Phase structure of dynamic dependences $C_0/\Gamma_0(T)$ (up) and Q(T) (down) during one cardiac cycle, normal hearts – green lines, HCM hearts – black lines (red bars show the significant difference between normal and HCM patients, $p<0.05$).

When measuring the same parameters in patients with HCM, overgrowth of myocardiaum of left ventricular free wall prevented the jet twisting when filling the cavity of the left ventricle. This is reflected in the phase composition of the curve $C_0/\Gamma_0(T)$. The value of C_0/Γ_0 after the opening of the mitral valve was significantly lower due to the decrease of the azimuthal velocity component. This leads to a lack of jet spin and a significant decrease in the volume of tornado-like jet ejected into the aorta during the systole.

4. Discussion

Used structural criteria of intracardiac blood flow state allows link establshment between the geometric configuration of the left ventricular cavity and architectonic trabecular layer covering the streamlined cavity surface on the one hand, and the blood flow velocity field generated in the cavity and ejected in the aorta, on the other hand. This link discloses the jet formation mechanism within the heart and allows the use of formal quantitative criteria for evaluating the effectiveness of cardiac output. Calculation of the proposed flow parameters in patients with severe HCM showed that these criteria reflect adequately the dynamics of the jet evolution in the cavity of the left ventricle. It becomes clear that the decline in cardiac jet ejected into the aorta during the systole is due not only to a decrease in the cavity volume, but also to the lack of a jet swirling during diastolic filling of the left ventricle.

This allows the use of the proposed criteria in different variants of left ventricular remodeling for the quantitative assessment of intracardiac flow and cardiac output efficiency, and the extent of ventricle remodeling.

5. Conclusion

A new quantitative criteria of intraventricular flow has been shown to reflect the statement of intracardiac hemodynamic and the extent of left ventricular remodelling, using the exact solution of nonstationary hydrodynamic equations for the class of Tornado-like viscous flows, in normal and HCM patients. The use of proposed criteria should be useful for diagnostics of all types of pathologic heart remodelling.

Acknowledgements

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