Tornado Concept of the Blood Flow Movement in the Heart and Main Vessels

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Abstract
The article proposes a new approach to the quantitative analysis of the hydrodynamic structure of blood flow in the flow channel, from the left atrium to the end of the aorta. This approach is based on the use of the concept of self-organization of tornado-like swirling jets in channels of a certain geometric configuration, for which exact solutions of the basic non-stationary equations of hydrodynamics had been found. Based on a large amount of experimental data, it was shown that the necessary and sufficient conditions for generating and maintaining the swirling structure of the jet throughout the entire cardiac cycle are satisfied throughout the channel under consideration. It is shown that the swirling flow structure is the main factor acting in the mechanism of blood movement, ensuring the stability of the flow structure, the absence of stagnant and separation zones and minimizing the viscous interactions in the flow core and at the flow boundaries.

Keywords
tornado-like flows of a viscous medium, exact solutions of non-stationary equations of hydrodynamics, heart, aorta, blood flow

Abbreviations
PA – pulmonary veins
LA – left atrium
LAA – left atrium appendage
LV – left ventricle
MV – mitral valve
AV – aortic valve
PM – papillary muscles

Introduction

The stability and high energy efficiency of the blood flow in the heart and the main arteries of the body does not have sufficient theoretical justification. The reasons for this are the complex geometric configuration of the flow channel, which has movable boundaries throughout, the changing parameters of the rheological state of the blood, and the biological instability of the systems involved in the mechanism of blood movement. Significant difficulties are associated with the experimental study of blood flow - dynamic non-stationary parameters, the inability to visualize and take measurements with sufficient accuracy. Modern diagnostic systems can significantly expand the measurement capabilities, however, the reliability of the information received is often in doubt, and the interpretation of the results is hampered by the lack of a common agreed concept based on the quantitative characteristics of the flow.

Indeed, the body of knowledge accumulated over the centuries-old history of the study of blood circulation still does not answer the basic questions - what ensures stability, high regulatory and compensatory adaptability of the blood flow, how is the adequate distribution of blood in the regional circulation pools ensured, what type of flow blood flow, what is the energy balance of the flow, etc.

Meanwhile, a number of features of the blood flow registered phenomenologically do not have sufficient interpretation from the point of view of involvement in the mechanism of blood movement. Such features include the fact of strictly coordinated heart contraction, the presence of trabeculation on the streamlined surfaces of the heart, the hemodynamic significance of atrial contraction, the mechanics of the functioning of the heart valves, the fact that the blood flow swirls over a fairly long length of the channel, etc.

A multidisciplinary study of blood flow with the simultaneous use of data obtained by the methods of anatomical and physiological measurements, physical modeling of the flow, and comparison with existing hydrodynamic models of motion of viscous continuous media can be one of their approaches, which partially overcomes the difficulties that arise.

The purpose of this study, conducted at the Bakulev Research Center for more than 40 years, has been elucidating the role of swirling flow in the mechanism of blood movement and how to use this phenomenon to diagnose and treat circulatory disorders.

Hydrodynamic model

The study of blood flow is impossible without comparison with the types of flow known in hydrodynamics. Relatively well studied are laminar and turbulent flows. All previous studies of blood circulation were based on a comparison of blood flow with these classes of currents. However, the impossibility of formally determining the initial and boundary conditions, the rheological properties of blood, and taking into account the mobility of borders does not allow a systematic and reliable description of the field of velocities and pressures in the blood flow over a sufficiently large section of the channel. Attempts to simulate blood flow using numerical solutions of the Navier-Stokes equations in short sections allow reproducing fixed combinations of parameters, but they do not allow taking into account the well-known wide possibilities of regulation and compensation of blood circulation.

In our study, we used a hydrodynamic model that describes the structure of a swirling jet that occurs when a curved curved surface flows around it. These jets were discovered and experimentally investigated in the 70s of the last century [1]. They were called tornado-like jets (TLJ), and their structure was described using particular exact solutions of the unsteady hydrodynamic equations for this class of swirling flows of viscous continuous media [2].

Exact solutions of the Navier-Stokes equations and continuity reflect the laws of energy conservation and are applicable for the class of centripetal swirling flows that are universally observed in nature. In this case, any radially converging swirling flow can be exhaustively characterized in a cylindrical coordinate system in terms of the velocity vectors in the longitudinal (Vz), radial (Vr) and tangential (Vφ) directions (Fig. 1). Then the total flow rate is equal:

$$u_\Sigma = \sqrt{u_r^2 + u_z^2 + u_\varphi^2}$$

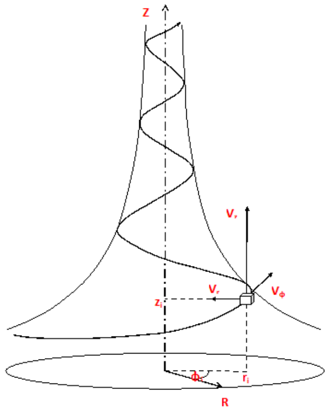

Figure 1. Schematic representation of a swirling jet with a designation of the direction of the coordinate axes and vectors of the velocity components.

The structure of a single tornado-like jet having one circulation is described in terms of exact solutions by the following expressions:

$$\begin{cases} u_r = -C_0(t) * r; \\ u_z = 2 * C_0(t) * z; \\ u_\varphi = \dfrac{\Gamma_0(t)}{2 * \pi * r} * \left(1 - e^{\frac{-C_0(t) * r^2}{2 * \nu}}\right) \end{cases}$$

In the above relations, uz is the longitudinal, ur is the radial and u? are the azimuthal velocity components, $C_0(t)$ is the radial velocity gradient [sec-1], $\Gamma_0(t)$ is the jet circulation [m2 / sec]; $C_0(t)$, $\Gamma_0(t)$ are independent time functions that change due to the non-stationary flow, ν is the kinematic viscosity of the medium [m2 / s].

These expressions repeat the structure of the Burgers vortex [3] with the difference that they take into account the possibility of unsteadiness of the jet due to the time variation of the quantities $C_0(t)$, $\Gamma_0(t)$ and geometric relationships in the flow channel.

The flows of this class have characteristic properties that distinguish them from other types of flows (including swirling).

1. These flows are carried out along predetermined streamlines, the geometric configuration of which is formally defined and shown in Fig. 1.
2. Flows of this class differ from laminar and turbulent flows by the weak effect of viscosity on the structure of the velocity field and, therefore, the minimization of shear stresses, high stability due to the inertia of the rotation of the jet, and the absence of tear-off and stagnant zones provided that the dynamic configuration of the flow channel corresponds to the instantaneous directions of streamlines and the need for special structural organization of the boundary layer, which is a combination of vortex formations, I provide pair the main stream and the walls of the flow channel on the bearing type.
3. Initiation and maintenance of the flow is possible if the necessary and sufficient conditions arising from the exact decisions are met. This is the presence of a concave surface streamlined by the medium at a sufficient speed, ensuring the convergence conditions of the jet (for example, in the confuser channel), providing conditions for the formation of a moving vortex boundary layer.
4. In the flows of this class there is no transverse transfer of the medium, because all streamlines are directed toward the axis of the jet.

The successful use of tornado-based technologies based on precise solutions in a number of technical devices has made it possible to significantly reduce aerohydrodynamic drag on streamlined surfaces and channels, intensify heat

and mass transfer, increase the stability of streamlined surfaces, etc.
Exact solutions allow us to determine the structural parameters of a swirling jet, characterizing its dynamic state and obtained from the geometric characteristics of the jet. Assuming that the jet occupies most of the volume of the flow channel, instead of the geometric characteristics of the jet, the geometric characteristics of the flow channel can be used, i.e. heart and aorta.

So, based on the analysis of the dynamic geometric configuration of the flow channel, specific quantitative indicators characterizing the state of the swirling jet in the coordinate system associated with it can be calculated. In this case, it becomes possible to determine the instantaneous position of the origin corresponding to the point of jet initiation; calculate the trajectory of the streamlines of a swirling jet; relative to the longitudinal coordinate of the movable flow channel; calculate the volumetric index of the jet equal to the product of the longitudinal and square radial coordinates ($z_i r_i^2$) in the moving cylindrical coordinate system of the jet and its dynamics during the cardiac cycle; determine the function $C_0(t)$, which is the frequency characteristic of the rotation of the jet; determine the function $\Gamma_0(t)$, which is the circulation of the jet; calculate the ratio of these functions, which reflects the degree of swirling of the jet; determine the curvature of the streamlined surface on which the jet is initiated; calculate jet power up time.

For each of the listed indicators, calculation methods have been developed [4,5,6,7].

Methods

The difficulties of experimental studies and analysis of swirling flows are primarily associated with the need for complex stereometric measurements and reconstructions, since the structure of the flow is directly related to the unsteady geometric configuration of the channel from the left atrium to the end of the aorta.

The first studies were carried out on the basis of morphometry of casts of the cavities of the heart and aorta, made in such a way as to preserve, if possible, the natural geometric configuration of the flow channel. The reliability of this method suffers due to the inability to exclude posthumous changes in geometry and the impossibility of recording dynamic transformations of the flow channel configuration during cardiac contraction.

The appearance of MSCT made it possible to carry out similar measurements on dynamic images of the flowing cavities of the heart and aorta, and the high spatial resolution of this method made it possible to analyze the spatial orientation and dynamic expression of intracardiac trabeculae in the cavity of the left ventricle.

A number of studies have been conducted using magnetic resonance methods. Thus, using phase-contrast MR-velocimetry, a mapping of the velocity field in the aorta was performed. The appearance of the 4D-Flow software package allowed us to visualize and compare with the expected directions of the blood flow stream lines in the cavity of the left atrium and left ventricle of the heart.

Angiographic methods were used to measure the movement of the aortic wall and determine the distribution of aortic compliance along its length. These measurements were subsequently confirmed by elastometric measurements of the radial elasticity of annular aortic specimens with a fixed longitudinal coordinate on a tensile testing machine.

Tornado-like jets were obtained and investigated in the form of built-in flows arising at the bottom of the recesses streamlined by a turbulent flow. In our studies, these jets are enclosed within the boundaries of channels, which can significantly affect the flow structure. To demonstrate the very possibility of obtaining such jets and to study the advantages of tornado-like streams over streams of other classes, a hydrodynamic bench was constructed, providing for the possibility of comparing channels of various geometric shapes. The streams formed in these channels were visualized using dye.

Experimental studies were accompanied by a deep theoretical study of exact solutions, as a result of which methods were developed to calculate the structural parameters of swirling jets that occur in the cavities of the heart and aorta.

Results

1. The directions of blood flow in the cavity of the left atrium were studied by the method of selective staining of flows on images obtained by MRI 4D-Flow and MSCT with contrasting in patients without visible cardiodynamic disturbances [7]. It was shown that during the filling phase of the medicinal product, the curvature of the dome forms a concave surface, under which a swirling flow arises, fed by four medicinal products. In this case, the directions of the jets coming from the drug do not intersect and form a spirally organized stream, swirling clockwise in the direction of the mitral valve. The flow as a whole is directed tangentially to the surface of the dome and ensures blood flow from the drug due to the dynamic pressure gradients arising in the swirling flows. The curvature of the streamlined surface of the PL during the emptying phase qualitatively corresponds to the curvature of the forming surface forming the streamline of the jet, which coincides in size with the jet filling the LV. At the same time, there is a reduction in LAA ejecting a portion of blood in the direction of the flow swirl. The contraction of LAA maintains the continuity of rotation of the residual mass of blood in the LA cavity between contractions. Additional evacuation of blood from the drug at the end of the LV filling phase (slow filling phase) is provided by dynamic gradients that arise in the intensively swirling flow in the LV cavity.

An analysis of the directions of the streamlines and a comparison of these directions with the movement of the wall shows that the contraction of the left atrium does not change the orientation of the streamlines, i.e. systole of LP is hemodynamically insignificant and provides only constant concavity of the streamlined surface, thus supporting the conditions for the formation of a swirling flow and eliminating episodes of wall prolapse during rapid emptying of the left atrium during the phase of rapid LV filling.

2. During a stereometric study of LV casts, geometric heterogeneity of intracardiac structures flowed around by blood was found. As a result, a group of trabeculae was identified, located mainly on the free and front walls of the LV cavity, which together form a system of converging spiral-oriented guides twisted clockwise along the axis connecting the center of the MV and some point located in the apical part of the cavity, but not coinciding with the apex . An alternative guide system consists of trabeculae of the anterior-septal angle and PM, which are oriented along a converging spiral (also twisted clockwise) along the axis connecting a point located in the lower third of the free LV wall and the center of the AV.

It was suggested that the contraction of the trabeculae of both systems (and, therefore, their expression in the blood stream) occurs in an alternative mode, while the trabeculae of the free wall form the structure of the jet filling the LV cavity, and the trabeculae of the anterior-septal angle and PM form the structure of the jet, expelled from the LV cavity into the aorta. Subsequently, these data were confirmed by analyzing dynamic images of the LV cavity using MSCT ventriculography with contrast. In these images, the alternative functioning of both systems of trabeculae is clearly visible [8,9].

As a result of these observations, the orientation of both systems of guiding trabecular lines relative to its own axis were calculated and the value of the ratio of time-dependent functions C_0/Γ_0 was calculated. It was shown that the obtained value varies according to the hyperbolic law depending on the total longitudinal coordinate along the evolution path of the jet (i.e., as a result of summing the axis length along the inflow and expelling systems of trabeculae), which suggests that the evolution of a single swirling jet occurs retaining its structure when changing phases of diastole and systole of the ventricle [10,11].

In the development of these results, a comparative anatomical study of the left ventricular casts of animals with significantly different sizes was performed. So, a comparison was made of the trabecular relief on the casts of the left ventricle of rats, rabbits, dogs and humans. The dependences obtained earlier on human casts were reproduced with high reliability on smaller animals. This allowed us to conclude that the structure of the flow formed in the LV does not depend on the size of the cavity [6].

The study of the architectonics of the trabecular relief in patients with hypertrophic obstructive cardiomyopathy (CMP) before and after surgical correction in comparison with the normal location of the trabeculae according to dynamic MSCT-ventriculography with the help of showed that the graphs of the change in the value of the ratio C_0/Γ_0 depending on time during the cardiac cycle in normal and with CMP significantly different. With hypertrophy, the spin of the jet filling the LV cavity decreases, which leads to a significant reduction in cardiac output. Surgical correction of hypertrophy by myectomy by access from the right ventricle partially restores the normal mechanism of evolution of the swirling jet in the LV cavity [4].

Visualization of the jet in the LV cavity using MRI 4D-Flow confirms that the swirling jet enters through the MV in a swirling state, is directed towards the back wall of the cavity and swirls clockwise relative to the axis passing through the MV (providing additional evacuation of blood from the LP cavity). After the closure of the MV, this vortex unfolds with respect to the relatively large curvature of the LV free wall. This curvature (according to the ratio of radius and depth) qualitatively corresponds to the curvature of the generatrix of the surface, forming a swirling stream, expelled from the LV cavity into the aorta. At the moment of AK opening, this jet, without losing structure due to the inertia of rotation, rushes into the AK lumen and is injected into the aorta [10,11].

What is needed to implement this mechanism? Firstly, a clear separation of the dominant and secondary jets at the time of injection, which is ensured by the absence of transverse transport of the medium in a swirling jet. Secondly, the suction of the medium from the zone of the nucleation of the jet (in the left atrium when filling the LV, and in the LV when injecting into the aorta) due to the dynamic pressure gradient in the swirling stream. Thirdly, the justification of the possible absorption of smaller secondary flows by the dominant swirling jet, taking into account the possibility of the formation of ring vortices with known stability, recorded, in particular, by G. Pedrizzetti [12]. Fourth, the coincidence of the external contours of the cavity with the current lines of the tornado jet and the presence of a curved generatrix surface, which serves as the basis for such a jet. Fifth, the ubiquitous presence of conditions for the formation of a moving vortex boundary layer, which excludes the occurrence of shear stresses at the jet boundary [13]. In LV, normal and compensated pathology ensures the simultaneous fulfillment of these conditions.

Thus, the coordinated contraction of the streamlined structures of the LV cavity throughout the entire cardiac cycle corresponds to the instantaneous state of evolution of the intracardiac blood flow. At the same time, mechanisms are maintained to maintain circulation of the jet coming from the LA and the jet being expelled into the aorta. It is important to note that the valve apparatus in this case plays a passive role, ensuring the continuation of the movable boundary of the jet.

3. Unlike the heart, the aorta is not an actively contracting organ, but the mobility of its walls is important to maintain the structure of the tornado stream. The studies conducted were aimed at proving that the normal geometric shape of the aorta during the entire cardiac cycle ensures that the conditions for maintaining such a structure are met.

On the casts of the aorta of various animals (man, pig, dog, rabbit) it is shown that the radius of the flow channel varies along the length of the aorta in accordance with the laws arising from the exact solutions. This pattern is that, starting from the origin along the channel, the condition for the constancy of the product of the square of the radius and the value of the longitudinal coordinate is fulfilled. For the aorta, this condition is satisfied if the position of the origin is separated from the AV deep into the heart by a distance equal to the distance to the place of initiation of the swirling jet. Intravital measurements using MSCT and MRI showed that this value changes during the cardiac cycle in accordance with the logic of evolution of the jet, i.e. increases with open AV and decreases with closed AV. [5].

Using elastometric and angiographic measurements, it was shown that this pattern is performed with higher accuracy at a normal level of pressure in the aortic lumen. Pressure increase over 150 mm Hg leads to distortions of this dependence [5].

Using elastometric measurements, it was shown that normal aortic elasticity increases in the distal direction. At the same time, the general confusoriness of the aortic duct is preserved, however, the calculated position of the origin is mixed in the positive direction with the AV closed and in the negative direction with the AV open, when the jet in the LV cavity and in the aorta is a single unit. This distribution of elasticity along the aorta is also distorted with an increase in intraluminal pressure of more than 150 mm Hg. [14].

Mathematical modeling of a circular elastic channel with longitudinal radial dimensions of the human aorta confirmed a significant dependence of the possibility of forming a tornado-like swirling jet on the distribution of elasticity along the flow channel. [15].

Visualization of the flow in the aorta using MRI 4D-Flow shows a significant change in the degree of swirling of the jet depending on the phase dynamics of the AV. The degree of twist increases significantly with the valve closed [30].

Mapping and analysis of the velocity field in the aorta, measured using phase-contrast MR-velocimetry, revealed the following features of the flow: a) dominant rotation of the velocity vectors clockwise in the distal direction; b) the constant presence in each section of the aorta of at least two circulation centers of the opposite sign, corresponding to a dominant stream and secondary return jets with the same structure; c) rotation of the axis of the injected swirling jet in the aortic lumen (precession) clockwise throughout the cardiac cycle (the stream as a whole rolls along the aortic wall); d) a decrease in the value of the circulation of the stream and the frequency response of the stream C in the distal direction; d) a decrease in the amount of circulation Γ0 during the cardiac cycle (extinction of rotation). The conclusion is made about the need for a pulsating mode of exile to resume and maintain the rotation of the jet, like a whirligig [17].

Thus, during the entire cardiac cycle and throughout the aorta, the geometric conditions necessary to maintain the structure of the tornado jet are fulfilled.

Discussion

The above results allow us to draw a general conclusion that at all stages of the evolution of the blood stream from the left atrium to the aorta, the conditions formulated in exact solutions are met that are necessary and sufficient for the formation of a potential tornado jet. The reliability of this conclusion is ensured by the fact that the desired result is obtained using various measuring methods, in various conditions and in animals of various sizes.

Nevertheless, the question remains open of what advantages the blood flow acquires due to the tornado structural organization.

First of all, this is the potentiality of a swirling jet, the meaning of which is the absence of separated and stagnant zones, the absence of significant viscous interactions both in the flow core and at its boundary. Shear stresses in such flows are replaced by rolling stresses, which determines a low hydrodynamic resistance. For blood flow, minimizing viscous interactions in the core of the flow and at its border means the absence of interaction between blood components - biologically active molecules and shaped elements, as well as the absence of damaging shear effects on the wall of the flow channel, which also has biological activity. A pathological change in the configuration of the flow channel will inevitably lead to the appearance of excess shear stresses and the activation of the corresponding compensatory mechanisms aimed at restoring the continuous flow.

Another question that arises when using accurate solutions for analyzing blood flow is the question of whether the proposed formal description of the tornado-like flow is a purely theoretical model applicable only to an ideal fluid.

To answer this question, a series of bench hydrodynamic studies of jets arising in channels of various geometric shapes was carried out. These studies showed that the structure of the jet is determined by the geometric configuration of the channel. It was shown that the formation of a potential swirling jet, corresponding in structure to the structure of tornado-like jets, described by exact solutions, occurs in a channel having the form of a second-order hyperboloid (Fig. 2a), corresponding to the directions of streamlines obtained from exact solutions.

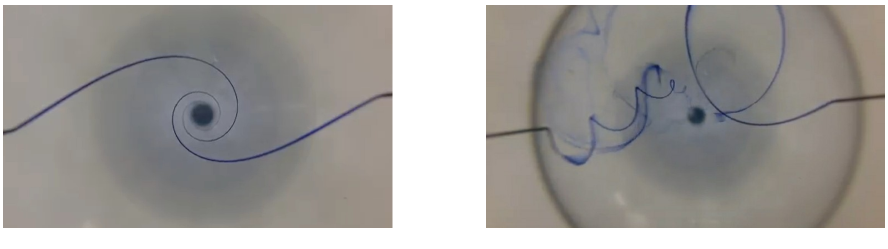

Fig. 2. a - visualization of a potential jet in a hyperbolic channel, bounded from above by a flat cutter; the gap between the cutter and the upper edge of the channel is 8 mm; b - visualization of jet pulsations with the formation of large-scale potential vortices in a hyperbolic channel with a cut-off in the form of a sphere segment; the gap between the cutter and the upper edge of the channel is 8 mm.

The combination of channels with a curved surface generates flow pulsations, accompanied by the appearance of large moving vortex formations, the structure of which also corresponds to the structure of tornado-like jets (Fig. 2b).

Thus, potential jets of a viscous medium exist and can be reproduced in a physical experiment.

An important question is the role of the flow swirl in the implementation of the circulatory function - the transfer of blood to organs and tissues.

The flooded tornado-like jet sews with the environment along the azimuthal velocity component, since only this component depends on the viscosity of the medium. This ensures the constant movement of the entire mass of blood in a limited space of the flow channel, eliminating the formation of stagnant zones and determines a more complete change of blood mass at each stage of the evolution of the jet.

The rotation of the jet creates a radial gradient of dynamic pressure (proportional to the square of the azimuthal velocity component), which ensures filling of the jet only from the side of its end and "suction" of the jet in the nucleation zone. Due to the radial gradient of dynamic pressure, a more complete evacuation of the medium from the zone of its nucleation occurs.

Due to the incompressibility of the liquid medium, the structure of the swirling jet extends to the entire available channel length faster than the jet manages to fill up with the medium. Therefore, in the aorta, the jet increases in volume from the axis of the canal to its periphery, providing a deterministic distribution of blood along the branches of the aorta due to the radial displacement of the secondary and return flows.

Conclusion

Thus, the blood flow in the heart and aorta represents a potential swirling flow, the structure of which can be described using exact solutions of the unsteady equations of hydrodynamics. This structure ensures the movement of blood with low hydrodynamic resistance, the absence of viscous interactions in the flow core and at its borders, and minimization of shear stresses.

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