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The influence of vortices on hemodynamics in blood vessels

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Abstract. Blood flow in vessels is affected by several factors like vessel shape, blood thickness, and heart function. Swirling patterns of flow, called vortices, are often seen in blood vessels and can affect how blood flows. This study aims to understand how vortices affect blood flow and the reasons behind these changes. Different instruments, like particle image velocimetry (PIV), computational fluid dynamics (CFD), and magnetic resonance imaging (MRI), were used to measure and analyze blood flow. CFD simulations were done using realistic blood vessel models to study how vortices form and how they affect blood velocity and pressure. The results show that vortices can cause significant changes in blood velocity and pressure, which can lead to changes in blood flow. The increased wall shear stress may contribute to the development of heart disease. This research highlights the importance of considering the impact of vortices on blood flow dynamics when designing and assessing cardiovascular devices and treatments.

Keywords: hemodynamic, vortices, computational fluid dynamics, velocimetry, magnetic resonance imaging.

1. Introduction

The cardiovascular system is crucial for delivering oxygen and nutrients to tissues and organs, with blood flow playing a critical role in this process. However, blood flow in vessels is not laminar, and vortices often form, affecting the flow characteristics of blood. Understanding these effects is vital for managing cardiovascular diseases and designing devices and treatments. To study the formation and evolution of vortices, computational fluid dynamics simulations were performed using ANSYS Fluent, based on realistic models of human blood vessels. The simulations considered the effects of blood viscosity, vessel wall elasticity, and heart function. Instruments such as optical coherence tomography (OCT) and particle image velocimetry (PIV) can also be used to study blood flow in the circulatory system, and CFD is a numerical approach for modeling fluid flow in complex geometries. Understanding the impact of vortices on blood flow is crucial for designing cardiovascular devices, treatments, and disease management.

2. Formation and characteristics of vortices

Vortices can form in blood vessels due to a variety of factors, including the presence of obstructions, changes in vessel diameter, and the presence of stenosis or aneurysms. Vortices can also be generated by the motion of the heart and the pulsatile flow of blood. The data used to support the vortex formation in principle can determine any biological fluid transport system, including the blood vessel and human heart [1]. The formation and characteristics of vortices are influenced by the Reynolds number, which

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is a dimensionless parameter that characterizes the flow regime in fluid dynamics. In blood vessels, vortices can be either steady or unsteady, and they can exhibit a range of sizes, shapes, and intensities.

2.1. Shear stress

Vortices are swirling patterns of fluid flow that can form in the blood vessels due to various factors such as geometric constraints, cardiac pulsation, and external forces. These vortices can significantly impact hemodynamics, which is the study of blood flow and its relationship to the circulatory system.

One of the ways vortices can influence hemodynamics is by affecting the wall shear stress, which is the frictional force between the blood and the vessel wall. Wall shear stress is known to play a crucial role in various biological processes such as blood clotting, inflammation, and atherosclerosis. Vortices can either increase or decrease the wall shear stress, depending on their direction and intensity. For various Re, Figure 1 has demonstrated the impact of spiral flow on wall shear stress. As the Reynolds number rises (indicating an increase in spiral flow), the wall shear stress along the pipe also increases [2], as shown in Equation (1).

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial y}\right) = 6h\frac{\partial}{\partial x}(U_1+U_2)h + 6(U_1-U_2)\frac{\partial h}{\partial x}+12\frac{\partial h}{\partial t} \qquad (1)$$

The flow of a lubricant in a narrow gap is described by the classical Reynolds equation, which serves as a fundamental basis for the classical theory of lubrication. The pressure distribution and the lubricant thickness h are the most important two parameters [3].

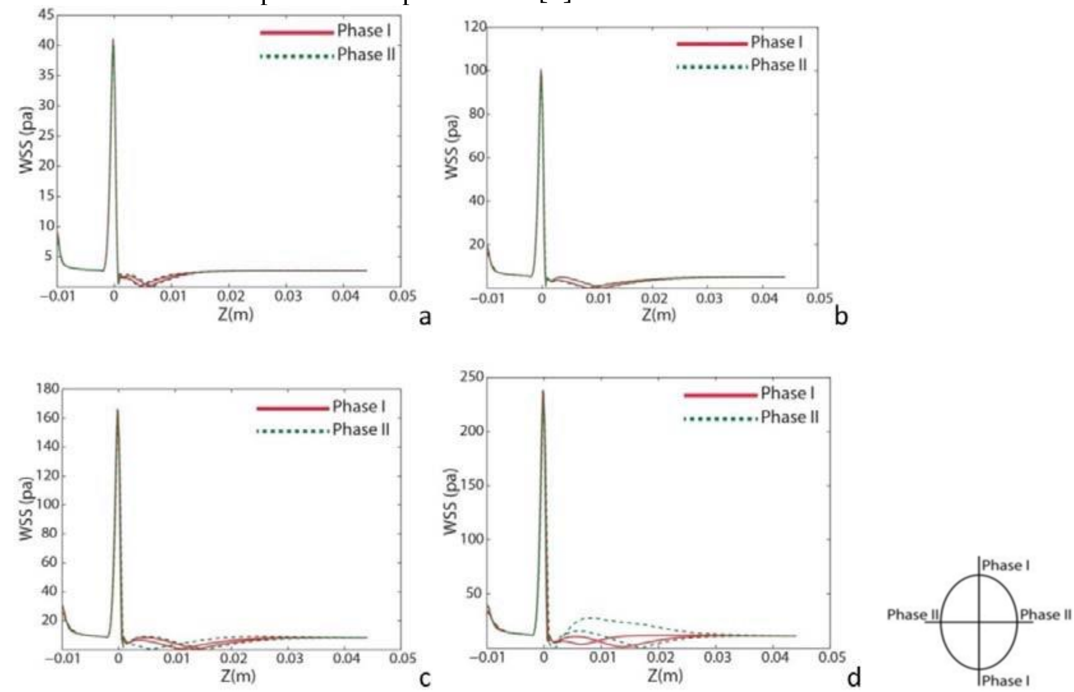

Figure 1. The wall shear stress at various stages for Reynolds numbers of (a) 500, (b) 1000, (c) 1500, and (d) 2000.

2.2. Impact on blood flow and pressure

Another way vortices can impact hemodynamics is by altering the flow field, which can lead to the formation of recirculation zones, separation zones, and areas of turbulence. These changes can influence the distribution of oxygen and nutrients to the tissues and a rise in the possibility of thrombus development, which is the formation of a blood clot.

The hemodynamics inside blood vessels can be significantly impacted by the existence of vortices in the vessels. For example, vortices can alter the direction and velocity of blood flow, which can impact

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the distribution of blood to different regions of the body. Additionally, vortices can also increase the turbulence of blood flow, which can result in more pressure drop and shear stress on the vessel walls. This can have negative consequences for the health of the cardiovascular system, including increased risk of stenosis, aneurysm formation, and thrombosis.

Figure 2 demonstrates the effect of spiral flow on the model artery's central total pressure. At the axial position of the stenosis (0m), a substantial pressure drop is observed. However, from 0.1m inwards along the artery, the pressure remains nearly constant. While there is a slight rise in pressure in the post-stenotic region at higher Reynolds numbers (Re = 2000), the impact of the Reynolds number or spiral velocity component in that downstream section is negligible [2].

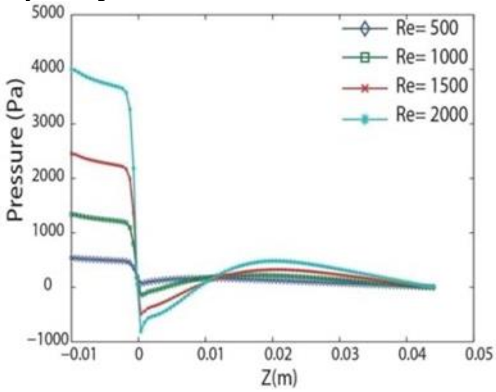

Figure 2. The total pressure at the centerline at various axial positions for different Reynolds numbers.

3. Diagnostic and therapeutic applications of vortices

Despite the potential drawbacks of vortices in blood vessels, they also have potential benefits for diagnostic and therapeutic purposes. For example, the presence of vortices can indicate the presence of obstructions or changes in vessel diameter [4, 5], which can be useful for diagnosing cardiovascular diseases. Additionally, vortices can also be used as a therapeutic tool to improve blood flow and prevent the formation of stenosis or aneurysms. For example, the introduction of targeted vortices into blood vessels can be enhances the transport of nutrients and oxygen to the tissues and organs, or to promote the removal of waste products from the bloodstream.

There are various techniques that can be used to study the influence of vortices on hemodynamics, including particle image velocimetry (PIV), computational fluid dynamics (CFD), and Magnetic resonance imaging (4D-flow MRI). Each of these techniques has its own strengths and limitations, and the exact research question and the needs of the study will determine the technique to use.

3.1. Particle image velocimetry (PIV) detection

PIV is a common instrument in fluid mechanics, a non-intrusive optical method for viewing three-dimensional flow fields. A standard PIV system includes of a high-speed camera, a laser with many high-power beams, and an optical setup that produces a light sheet from the laser's output light. Additionally, the synchronization between the laser and the camera is managed by a synchronizer [6].

The two primary techniques for determining point-by-point velocity are Hot-wire anemometry (HWA) and laser-Doppler velocimetry (LDV). HWA has a good signal-to-noise ratio, suitable for studying low-intensity turbulence and spectra. Another LDV suitable for high-intensity fluctuations and accurate timing [7, 8]. However, neither technique offers the ability to obtain spatial derivatives, visualize flow, or provide the spatial correlation capabilities that PIV offers. Therefore, it can be concluded that Figure 3 serves as a clear demonstration because of their critical significance in the field of modern experimental fluid mechanics [9].

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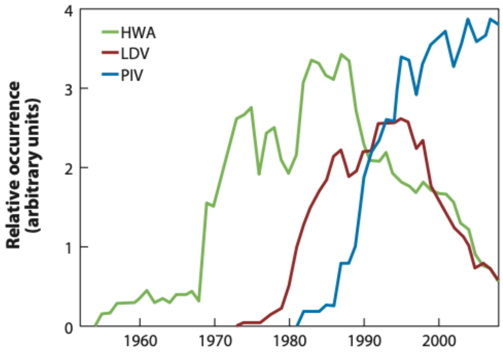

Figure 3. Emergence of Particle Image Velocimetry as Evidence from Google Ngrams for the Dominant Method in Experimental Fluid Mechanics.

Figure 3 shows that, from 1952 to 2008, the frequency of the trigrams hot wire anemometry (HWA), laser-Doppler velocimetry (LDV), and particle image velocimetry (PIV) was tracked on Google Books. Interestingly, a prior review on PIV was published in this publication at a period when none of the three primary measurement methods appeared to have a definite prevalence. However, PIV has become the approach of choice in experimental fluid mechanics over the last two decades. These findings were obtained from data gathered through Google Ngrams.

PIV is a versatile technique that is widely used in academic and industrial research, particularly in the fields of fluid mechanics and aerodynamics. However, studying turbulent flows with PIV can be difficult due to the complexity of these flows, which involve a variety of length and velocity scales, instability, and three-dimensional character. Despite these challenges, PIV can capture complex flow fields with high spatial and temporal resolution, providing detailed insights into flow structures. As a non-intrusive technique, PIV does not require physical probes or sensors to be inserted into the flow, minimizing disruptions to the flow and reducing the risk of equipment damage. PIV can also provide quantitative measurements of flow parameters such as velocity and vorticity, which can be used to validate numerical simulations and improve our understanding of fluid dynamics. However, applying PIV to highly turbulent flows or flows with large spatial or temporal variations can be challenging and may lead to measurement errors. The accuracy of PIV measurements can also be affected by factors such as particle size, seeding density, and camera resolution [9]. Despite these limitations, PIV remains a valuable tool for studying fluid dynamics in a wide range of applications.

Currently, PIV is widely used in academic and industrial research, particularly in the fields of fluid mechanics and aerodynamics. However, there is still room for improvement in terms of accuracy and applicability to a wider range of flow conditions. Kaufmann et al. employed PIV to confirm the accuracy of a CFD model that simulated flow distribution during cardiopulmonary bypass, which was influenced by the placement of the outflow cannula [6]. The results of the CFD investigation were validated within a 10% margin of error against the PIV results (Figure 4).

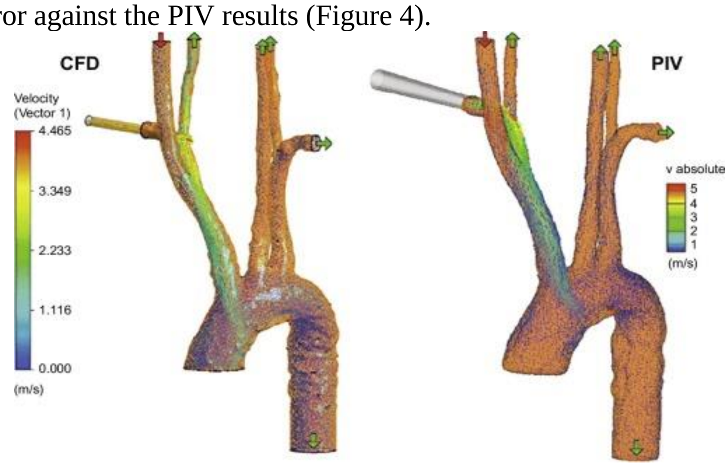

Figure 4. A comparison between the results obtained through CFD and PIV.

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Future development in PIV technology may focus on improving the accuracy and reliability of measurements, increasing the speed and efficiency of data processing, and expanding the range of flow conditions that can be studied, Additionally, advances in camera and laser technology may make PIV more accessible and cost-effective for a wider range of applications.

3.2. Computational Fluid Dynamics (CFD)

CFD is a numerical technique that uses conservation equations such as the continuity and Navier-Stokes equations to compute physical properties of fluid flow. It has become increasingly popular in the medical field due to advancements in diagnostic imaging. CFD simulations for vascular diseases involve six stages, including medical imaging, mesh generation, and visualization. Boundary conditions are critical for accurate results and can be obtained through patient-specific data, population data, or physiological assumptions and models. Multi-scale modeling is another approach that holds great potential but presents challenges such as deriving mathematical models of peripheral blood flow and designing robust interface conditions. Despite these challenges, CFD and multi-scale modeling can aid in understanding hemodynamics and fluid-structure interactions in vascular diseases [10].

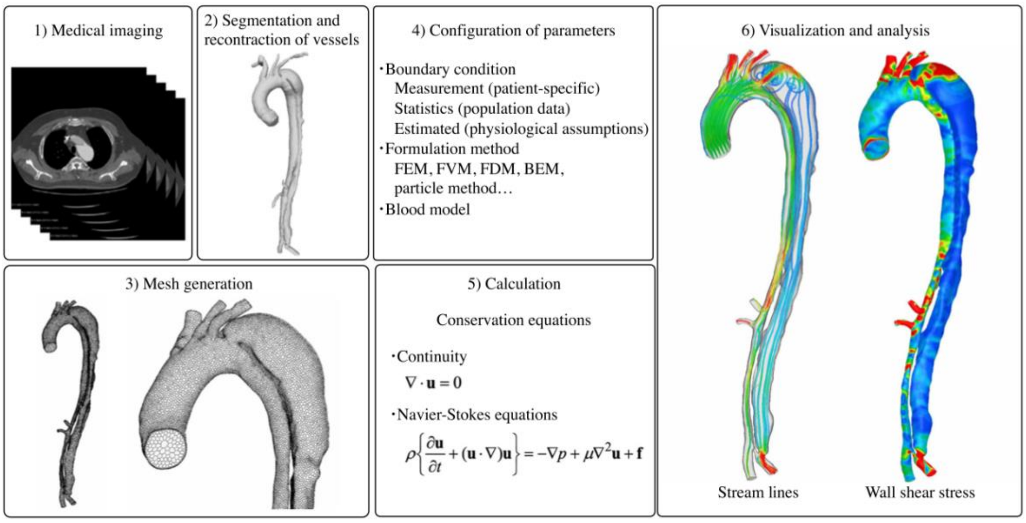

Figure 5. The six-stage procedures for CFD simulations of vascular diseases.

CFD is a way to understand how blood flows through blood vessels. A shown in Figure 5, there are six steps involved: (1) taking medical images, (2) creating a 3D model of the blood vessels, (3) breaking the model into small parts (meshing), (4) setting up important factors like how the blood moves and interacts with the vessels, (5) running calculations to see how the blood flows, and (6) analyzing the results with visuals like streamlines and wall shear stress (WSS).

The use of CFD has become more significant in the medical field because it can provide crucial information about blood flow dynamics and its potential use in medical device development, while reducing the cost and time required for experiments [11]. CFD is particularly helpful for investigating specific blood flow changes and the possibility of thromboembolism in regions like the hinge region, which can be challenging to observe experimentally. With recent advancements in fluid structure interaction analysis, CFD can now also explore the behavior of valve leaflets during opening and closing, further expanding its applications in medical research and development [12, 13].

CFD simulations showed that vortices in blood vessels can alter velocity and pressure profiles, causing recirculation and stasis. The formation of vortices was influenced by vessel geometry, viscosity, and wall elasticity. More complex geometries resulted in more vortices, while higher viscosity and wall elasticity led to more stable vortex structures.

3.3. Magnetic resonance imaging (4D-flow MRI)

Color Doppler is a crucial component of MRI, which has led to the development of a new technique called four-dimensional flow MRI. This method is an extension of three-dimensional phase-contrast MRI (PC-MRI) that tracks changes in blood flow and measures it in real-time. To create a customized model for individual patients, PC-MRI or ultrasonography can be used to match flow velocity in simulations. However, statistical averages can only provide generalized analysis data and cannot be patient specific.

Four-dimensional flow MRI allows for a study of the flow rate at any cross section during post-processing without requiring during acquisition, a cross-sectional habitat (Figure 6). For accurate extraction of vascular and flow volume, a high intravascular signal-to-noise ratio (SNR) is essential [14]. This can be done by combining steady-state free precession pictures with gadolinium contrast-enhanced magnetic resonance angiography (MRA) combined with flip angle and contrast media injection adjustments. By employing these methods, the accuracy of measurements using 4D-flow MRI can be improved [15-17].

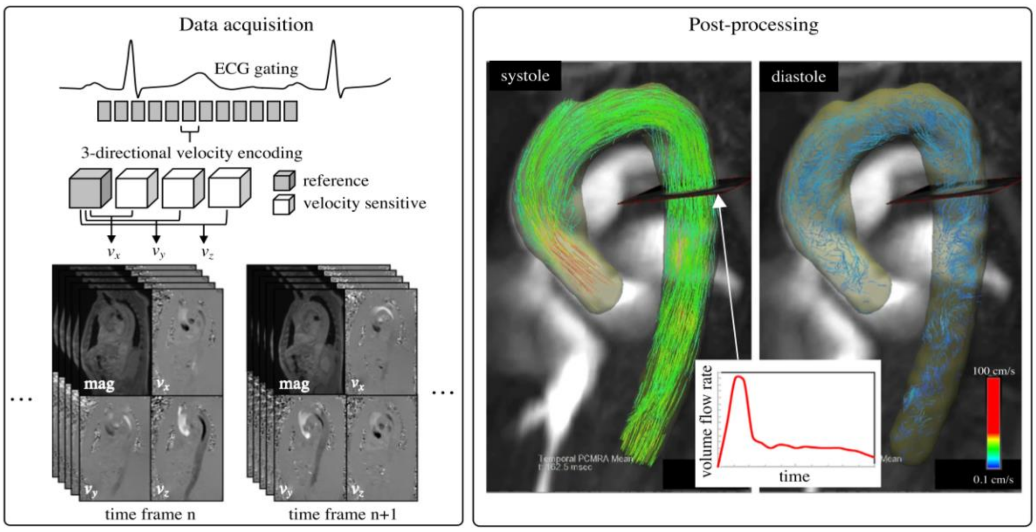

Figure 6. 3D phase contra data with time resolution through 4D-flow MRI.

Figure 6 shows 4D-flow MRI data that captures time-resolved 3D velocity data synchronized with the heart's cycle. This provides three velocity-encoded images and one reference image for each time frame of the heart. The data is used to reconstruct blood flow velocities and generate three data sets representing blood flow velocities along the x, y, and z axes combined with anatomic magnitude data. Software is used to process the data by correcting for background phase, segmenting the target vessel of interest, and performing phase antialiasing, allowing for retroactive flow analysis and visualization of the 3D flow structure.

4D-flow MRI predict the risk of cerebral aneurysm enlargement and rupture by measuring WSS [18], but this method has lower spatial resolution compared to CFD and may not accurately assess WSS [19]. Therefore, CFD is better suited While other methods should be combined to determine boundary conditions for thorough blood flow analysis.

Patient-specific CFD has been used to assess the risk of aortic dissection, focusing on factors such as Using 4D-flow MRI, WSS and pressure are challenging to investigate in depth [20-25]. According to CFD studies, thrombi typically form in places with low WSS and stagnant flow, whereas high WSS is a significant risk factor for false lumen expansion and retrograde type A dissection. A pressure imbalance that results in a reduction in the true lumen and maperfusion syndrome has been shown to be caused by desynchronized pressure gradients, according to research that measured pressure gradients between the true and false lumens in patients with TBAD. For the purpose of evaluating the risk of

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TBAD, a blood flow simulation model utilizing both 4D-flow MRI and CFD has also been proposed [15-17].

4. Results

Vortices can form in blood vessels due to various factors, including geometric constraints, cardiac pulsation, and external forces. Vortices can significantly impact hemodynamics, affecting the wall shear stress, flow field, and pressure. Vortices can either increase or decrease the wall shear stress, depending on their direction and intensity. Additionally, vortices can alter the flow field, which can lead to the formation of recirculation zones, separation zones, and areas of turbulence. These changes can influence the distribution of oxygen and nutrients to the tissues, and the possibility of thrombus development. Despite the potential drawbacks of vortices in blood vessels, they also have potential benefits for diagnostic and therapeutic purposes. For example, the presence of vortices can indicate the presence of obstructions or changes in vessel diameter, which can be useful for diagnosing cardiovascular diseases. Additionally, vortices can also be used as a therapeutic tool to improve blood flow and prevent the formation of stenosis or aneurysms. Various techniques can be used to study the influence of vortices on hemodynamics, including particle image velocimetry (PIV), computational fluid dynamics (CFD), and Magnetic resonance imaging (4D-flow MRI).

5. Conclusion

The study has significant implications for understanding the mechanisms underlying the development of cardiovascular diseases such as atherosclerosis, thrombosis, and aneurysm formation. The results suggest that vortices play a critical role in altering blood flow patterns and influencing hemodynamics, which can lead to negative consequences for cardiovascular health. However, the study also highlights the potential benefits of vortices for diagnostic and therapeutic applications. The presence of vortices can serve as a useful diagnostic tool for detecting obstructions or changes in vessel diameter, while targeted introduction of vortices can be used as a therapeutic tool to improve blood flow and prevent the formation of stenosis or aneurysms.

The results of studies using these various instruments and techniques have shown that vortices can have a substantial effect on the dynamics of blood flow in blood vessels. For example, studies using OCT have demonstrated that vortices can lead to the formation of regions of low and high blood velocity within the circulatory system. PIV studies have shown that vortices can lead to increased turbulence and fluctuations in fluid velocity, which can have negative effects on the delivery of oxygen and nutrients to the tissues.

In summary, vortices can form in blood vessels due to various factors and their characteristics are influenced by the Reynolds number. These vortices can impact hemodynamics by altering the flow field, wall shear stress, and leading to the formation of areas of turbulence, recirculation, and separation zones. While the presence of vortices in blood vessels can have both negative and positive consequences. It is possible to analyze their impact on hemodynamics using techniques like particle image velocimetry, computational fluid dynamics, and magnetic resonance imaging. To fully comprehend how vortices affect hemodynamics and how they might be used in clinical practice, more study is required. Overall, the study of vortices in blood vessels and their influence on hemodynamics is an important area of research with potential implications for the detection and treatment of heart disorders.

The formation and impact of vortices on blood flow dynamics are complex phenomena that can be studied through various imaging and measurement techniques. Future research can explore improving existing techniques or developing new ones, such as CFD, optical imaging, and nanoscale imaging, to better understand and minimize the negative effects of vortices. A multidisciplinary approach is necessary, drawing on expertise from fields like fluid mechanics, cardiovascular physiology, and biomedical engineering. By understanding and addressing the influence of vortices on fluid dynamics, researchers can develop more effective diagnostic and therapeutic tools for improving cardiovascular health.

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