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PHYSICAL LAWS OF BLOOD FLOW: BIOPHYSICAL FOUNDATIONS OF HEMODYNAMICS AND THEIR CLINICAL SIGNIFICANCE

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Abstract. This review article analyzes the biophysical foundations of hemodynamics and the mechanisms of blood flow governed by fundamental physical laws based on contemporary scientific literature. The roles of the Bernoulli, Poiseuille, Reynolds, Frank–Starling, and Laplace principles in the regulation of energy exchange, blood flow dynamics, vascular resistance, and cardiac function within the circulatory system are discussed. Furthermore, the effects of these laws on blood flow velocity, pressure gradients, blood viscosity, vascular wall tension, and the pumping function of the heart are examined from a scientific perspective. The literature analysis highlights the significance of hemodynamic principles in explaining both the physiological and pathological processes of the cardiovascular system, as well as their application in Doppler echocardiography, hemodynamic monitoring, and other modern diagnostic techniques. The findings indicate that the physical laws underlying hemodynamics provide an essential theoretical framework for the diagnosis of cardiovascular diseases, the interpretation of their pathophysiological mechanisms, and evidence-based clinical decision-making.

Keywords: hemodynamics, biophysics, blood flow, Bernoulli principle, Poiseuille law, Reynolds number, Frank–Starling law, Laplace law, vascular resistance, Doppler echocardiography.

INTRODUCTION

The cardiovascular system is a complex biological network responsible for maintaining the vital functions of the human body, and its operation is fundamentally governed by the physical principles of blood flow. Cardiovascular diseases remain one of the leading causes of morbidity, disability, and mortality worldwide. The development of pathological conditions such as arterial hypertension, ischemic heart disease, heart failure, atherosclerosis, and thrombosis is closely associated with alterations in key hemodynaamic parameters, including blood flow velocity, vascular resistance, blood viscosity, and arterial pressure.

Hemodynamics is an interdisciplinary field that investigates the physical principles governing blood circulation and integrates concepts from biophysics, physiology, cardiology, and biomedical engineering. The study of energy exchange within the bloodstream, the mechanisms underlying vascular resistance, the development of laminar and turbulent flow patterns, the pumping function of the heart, and the distribution of mechanical forces within vascular walls provides a comprehensive understanding of both normal and pathological cardiovascular processes. Hemodynamic phenomena observed within the circulatory system are governed by fundamental physical principles, including the Bernoulli principle, Poiseuille law, Reynolds number, Frank–Starling law, and Laplace law. These principles provide a scientific framework for explaining the complex relationships among blood flow, pressure, vascular resistance, blood viscosity, and cardiac function.

The widespread application of Doppler echocardiography, angiography, hemodynamic monitoring, and other invasive and non-invasive diagnostic techniques in modern cardiology has further emphasized the need for a detailed understanding of the physical characteristics of blood

flow. Moreover, hemodynamic models play a crucial role in the interpretation of diagnostic parameters, prediction of pathological changes, and development of innovative medical technologies.

The aim of this review is to analyze the physical laws governing blood flow and their manifestations in hemodynamic processes based on contemporary scientific literature, to elucidate the biophysical foundations of the Bernoulli, Poiseuille, Reynolds, Frank–Starling, and Laplace principles, and to substantiate their significance in assessing cardiovascular function, explaining pathological conditions, and supporting clinical diagnosis.

MATERIALS AND METHODS

This study was conducted using a literature review methodology. The information base consisted of scientific publications addressing hemodynamics, the biophysical foundations of blood flow, and the fundamental physical principles governing cardiovascular function.

The literature search and selection process was performed using the international scientific databases PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, and eLIBRARY. The search strategy was based on the keywords “hemodynamics,” “blood flow,” “Bernoulli principle,” “Poiseuille law,” “Reynolds number,” “Frank–Starling mechanism,” “Laplace law,” “cardiovascular physiology,” “vascular resistance,” and “clinical hemodynamics,” as well as their various combinations.

The analysis primarily included research articles, monographs, textbooks, and clinical guidelines published between 2015 and 2025. In addition, classical foundational sources that established the theoretical framework of hemodynamics were reviewed. The selection of literature was based on its relevance to the study topic, scientific reliability, and contemporary significance.

Analytical and integrative approaches were employed throughout the study. The theoretical foundations of the Bernoulli principle, Poiseuille law, Reynolds number, Frank–Starling law, and Laplace law, together with their roles in hemodynamic processes, were systematically examined. Based on the findings of the literature analysis, generalized scientific conclusions were formulated regarding the physical laws of blood flow and their significance in explaining the functional mechanisms of the cardiovascular system.

MAIN BODY

Physical Foundations of Energy in Blood Flow

Within the circulatory system, energy is manifested in three principal forms: pressure energy, kinetic energy, and gravitational potential energy. Pressure energy generated by the pumping action of the heart drives blood through the vascular network, whereas kinetic energy is associated with the velocity of blood flow.

The foundations of modern hemodynamics are closely linked to the work of the eighteenth-century physician and mathematician **Daniel Bernoulli**, whose scientific contributions extended across mathematics, physics, and astronomy. Bernoulli demonstrated that, in an ideal fluid flowing through a conduit without viscous or frictional energy losses, total energy is conserved and distributed among three interconvertible components: pressure energy, kinetic energy, and gravitational potential energy. In the cardiovascular system, pressure energy is generated by cardiac contraction and maintained by the elastic properties of blood vessels. Consequently, it is largely determined by cardiac output and vascular resistance.

The total energy of blood flow can be expressed by the following equation:

$$TE=P+\frac{\rho v^2}{2}+\rho g h$$

where: TE – total energy; P – pressure energy; ρ – blood density; v – blood flow velocity; g – gravitational acceleration; h – height relative to a reference level.

This equation describes the principle of energy conservation within the bloodstream and explains the relationship among vessel diameter, blood flow velocity, and pressure. In hemodynamics, it serves as a theoretical basis for understanding vascular stenosis, valvular abnormalities, and disturbances of blood flow.

Bernoulli Principle and Its Clinical Applications

The Bernoulli principle is based on the law of conservation of energy and describes the relationship among pressure, velocity, and height during fluid flow. According to this principle, the sum of pressure energy, kinetic energy, and gravitational potential energy remains constant at any point within the flow stream:

$$P+\frac{\rho v^2}{2}+\rho g h=\text{constant}$$

where: P – pressure energy; ρ – blood density; v – blood flow velocity; g – gravitational acceleration; h – height of the flow point.

The Bernoulli principle is widely applied in the assessment of valvular stenosis and vascular narrowing. For example, in aortic stenosis, a reduction in valve area increases blood flow velocity, resulting in a corresponding decrease in pressure distal to the stenotic region.

A particularly important application of the Bernoulli principle is found in **Doppler echocardiography**, where it is used to estimate pressure gradients from measured blood flow velocities. The modified Bernoulli equation is expressed as:

$$\Delta P=4V^2$$

where: **ΔP** – pressure gradient between two points of flow (mmHg); **V** – maximum blood flow velocity measured by Doppler ultrasound (m/s).

For example, if the maximum velocity across the aortic valve is 4 m/s, the pressure gradient can be calculated as follows:

$$\Delta P=4\times(4)^2=64 \text{ mmHg}$$

A pressure gradient of 64 mmHg indicates substantial resistance to blood flow across the aortic valve and is commonly considered a marker of severe aortic stenosis. Therefore, the modified Bernoulli equation represents a fundamental mathematical model in contemporary echocardiographic diagnostics and plays a crucial role in determining the severity of valvular heart disease.

The clinical significance of the Bernoulli principle extends beyond valvular disorders. It is also used in the evaluation of congenital heart defects, intracardiac shunts, pulmonary hypertension, and vascular stenoses. As a result, it remains one of the most important physical principles underlying modern cardiovascular diagnostics

Poiseuille Law and the Biophysical Basis of Vascular Resistance

Blood is not an ideal fluid; therefore, it loses energy, and consequently pressure, while overcoming resistance during flow. Vascular resistance is determined by several factors, including blood viscosity, vessel radius, and vessel length. The relationship among these variables is described by **Poiseuille's law**, which can be expressed as:

$$R=\frac{8\eta l}{\pi r^4}$$

where: R – vascular resistance; η – blood viscosity; l – vessel length; r – vessel radius.

Since blood flow is directly proportional to the pressure gradient and inversely proportional to resistance ($Q=\Delta P/R$), Poiseuille's equation can be rewritten as:

$$Q=\frac{\pi r^4 \Delta P}{8\eta l}$$

This equation demonstrates that vessel radius is the most influential determinant of blood flow because it is raised to the fourth power. Consequently, even minor changes in vascular diameter can produce substantial alterations in flow. For example, a 20% increase in vessel radius, while all other variables remain constant, nearly doubles blood flow. Similarly, the resistance of a coronary artery with a diameter of 2 mm is approximately sixteen times greater than that of an artery with a diameter of 4 mm.

Blood viscosity is another critical factor influencing vascular resistance. It is commonly denoted by η and measured in poise units. Because direct measurement of viscosity is relatively complex, it is often expressed relative to the viscosity of water. Plasma viscosity is approximately 1.7 times greater than that of water, whereas whole-blood viscosity is about three to four times higher. This difference is largely attributable to the presence of blood cells, particularly the hematocrit level.

It should be noted that Poiseuille's law provides only an approximate estimate of vascular resistance in the circulatory system. The equation is based on several assumptions:

- fluid viscosity remains constant over time and space;
- the vessel is rigid and cylindrical;
- vessel length is substantially greater than its diameter;
- flow is steady, non-pulsatile, and laminar.

In the physiological circulation, most of these assumptions are not fully satisfied because blood flow is pulsatile, blood vessels are elastic, and blood viscosity varies under different conditions. Nevertheless, Poiseuille's law remains highly valuable because it identifies the principal physical determinants of vascular resistance and blood flow.

Among all segments of the mammalian circulatory system, the greatest resistance is generated at the level of the arterioles. Although capillaries possess a smaller radius than arterioles, their enormous number results in a substantially larger total cross-sectional area. Moreover, arterioles contain smooth muscle fibers that enable active regulation of vascular resistance, whereas capillaries lack a smooth muscle layer and therefore cannot actively control resistance.

Regulation of arteriolar resistance plays a fundamental role in maintaining arterial blood pressure, particularly under conditions such as hypovolemic shock, and in distributing blood flow among different organs through autoregulatory mechanisms. In general, a decrease in arteriolar resistance reduces systemic vascular resistance (SVR), leading to an increase in cardiac output. Simultaneously, pressure decreases proximal to the arteriolar segment and increases distally, thereby altering tissue perfusion and regional blood flow distribution

Reynolds Number and the Characteristics of Blood Flow

Blood flow within blood vessels, as in any hydraulic system, is generally smooth and orderly, with the fluid organized into an infinite number of concentric layers moving at different velocities. When a fluid such as blood flows along a solid surface, such as the vascular wall, frictional forces create a thin boundary layer adjacent to the wall where flow velocity is reduced. Consequently, a velocity gradient and shear forces develop between the layer in direct contact with the vessel wall and the central region of the flow.

When fluid particles move in parallel layers without crossing one another, the flow is referred to as **laminar flow**. Under laminar conditions, resistance is determined primarily by viscous forces. In such a flow pattern, the average velocity of the fluid is approximately one-half of the maximum velocity observed at the center of the vessel lumen.

In contrast, **turbulent flow** is characterized by the mixing of fluid particles between adjacent layers. Turbulent flow is inherently disordered and less energy-efficient because a portion of the flow energy is dissipated through eddies and vortices, resulting in what is known as **inertial resistance**. Under turbulent conditions, the relationship between pressure gradient and flow is no longer linear, as resistance increases with increasing flow velocity. Consequently, a greater pressure gradient is required to maintain adequate blood flow. Energy losses associated with turbulence represent one of the principal causes of pressure reduction distal to severe vascular stenoses.

The clinical significance of turbulent flow is multifaceted. First, turbulence generates audible vibrations that produce cardiovascular sounds, including heart murmurs and the **Korotkoff sounds** detected during indirect blood pressure measurement. Second, turbulence alters the relationship between blood flow and perfusion pressure. Because of increased energy dissipation, the relationship between perfusion pressure and blood flow deviates from the linear behavior predicted by Poiseuille's law, requiring higher pressures to sustain sufficient tissue perfusion.

The transition from laminar to turbulent flow can be predicted using the **Reynolds number**, which represents the ratio of inertial forces to viscous forces:

$$\mathrm{Re}=\frac{dV\rho}{\eta}$$

where: Re – Reynolds number; d – vessel diameter (m); V – blood flow velocity (m/s); ρ – blood density (approximately 1050 kg/m³); η – blood viscosity (approximately 0.004 Pa·s).

The Reynolds number is a dimensionless quantity.

Every hydraulic system possesses a **critical Reynolds number**, below which flow remains laminar. Near this threshold, a transitional zone exists in which flow exhibits characteristics of both laminar and turbulent motion. In a long, straight, unbranched tube with steady non-pulsatile flow, the following conditions generally apply:

- **Re < 2000** — laminar flow;
- **Re > 2000** — turbulent flow.

However, the critical Reynolds number depends on the geometry of the flow system and is therefore determined experimentally for specific conditions.

In the aorta, the transition from laminar to turbulent flow typically occurs at Reynolds numbers between 2000 and 2500. In vessels affected by atherosclerotic lesions or at vascular bifurcations, the critical Reynolds number may be substantially lower, allowing turbulence to develop even under physiological flow velocities. In cases of severe stenosis, turbulence may arise at Reynolds numbers several times lower than those predicted for an ideal straight tube.

The Reynolds equation is particularly valuable for identifying factors that influence flow characteristics. As indicated by the equation, high flow velocities, such as those observed in stenotic arteries, and larger vessel diameters increase the likelihood of turbulence. Vessel diameter plays a dual role because it appears directly in the equation and simultaneously influences flow velocity. According to the continuity equation, a reduction in cross-sectional area leads to an increase in velocity, thereby amplifying the effect of vessel diameter on the Reynolds number. In contrast, within the microcirculation, both vessel diameter and flow velocity are relatively low, resulting in predominantly laminar blood flow.

Overall, the Reynolds number provides a fundamental theoretical framework for understanding the transition between laminar and turbulent flow and has important applications in the assessment of vascular stenosis, hemodynamic disturbances, cardiovascular sounds, and tissue perfusion

Frank–Starling Law

Ventricular performance is primarily regulated by three major factors: **preload**, **afterload**, and **contractility**. Preload is defined as the passive tension or degree of stretch imposed on the ventricular walls immediately before the onset of systole and is commonly represented by intraventricular pressure or end-diastolic volume. This loading condition determines sarcomere length at the end of diastole and thereby influences the force of subsequent myocardial contraction.

According to the **Frank–Starling law**, the greater the passive stretch of myocardial fibers during diastole, the greater the active tension generated during systole. This mechanism reflects an intrinsic property of cardiac myocytes and operates independently of external neural stimulation or hormonal regulation. Consequently, an increase in preload enhances myocardial contractile force, leading to an increase in stroke volume and, ultimately, cardiac output.

The physiological significance of the Frank–Starling mechanism lies in its ability to match cardiac output to venous return. By automatically adjusting the force of contraction in response to changes in ventricular filling, the heart is able to maintain a dynamic balance between the volume of blood returning to the heart and the volume ejected into the circulation.

The Frank–Starling law emerged from the independent investigations of two pioneering physiologists. In the 1890s, **Otto Frank** conducted experiments on isolated frog ventricles and measured the pressure generated against an occluded aorta under varying preload conditions. His studies demonstrated that increases in end-diastolic volume were associated with higher systolic pressure and a greater maximal rate of pressure development (**dP/dt_{max}**).

Approximately two decades later, **Ernest Starling** obtained similar findings using a heart–lung preparation in anesthetized dogs. By carefully controlling heart rate, venous pressure, venous return, and arterial resistance, Starling demonstrated a direct relationship between ventricular filling and the force of myocardial contraction. Together, these investigations established one of the fundamental principles of cardiovascular physiology.

From a physiological perspective, there is no single universal Frank–Starling curve for the heart. Instead, a family of Frank–Starling curves exists, each determined by the prevailing afterload and the inotropic state of the myocardium. Changes in venous return move the operating point of the ventricle along a given Frank–Starling curve. In contrast, alterations in myocardial contractility or afterload shift the heart to a different curve altogether.

Cardiac output can be expressed as:

$$CO = SV \times HR$$

where: **CO** – cardiac output; **SV** – stroke volume; **HR** – heart rate.

Through the Frank–Starling mechanism, an increase in ventricular filling enhances stroke volume, thereby increasing cardiac output without requiring changes in heart rate. Clinically, this principle is essential for understanding cardiovascular adaptation during exercise, fluid therapy, hemorrhage, heart failure, and other conditions associated with alterations in venous return and ventricular function.

The Frank–Starling law therefore represents a fundamental autoregulatory mechanism that enables the heart to adapt continuously to changing circulatory demands and maintain hemodynamic stability under both physiological and pathological conditions

Venous System and Venous Return

In a healthy individual, approximately **50% of the total blood volume** is contained within the venous system (about 15% in the heart, 20% in the pulmonary circulation, 10% in the arteries, and 5% in the arterioles and capillaries). The venous system possesses a high capacitance, and veins are usually partially collapsed. Therefore, the venous circulation can accommodate large volumes of blood without a significant increase in pressure.

Because the cardiovascular system functions as a closed circulatory system, **venous return and cardiac output are closely related**. An increase in the volume of blood returning to the heart is one of the primary mechanisms responsible for the rapid increase in cardiac output. For example, activation of the sympathetic nervous system causes contraction of venous smooth muscle, which reduces venous capacitance and increases venous return, thereby enhancing cardiac output. Similarly, during physical exercise, rhythmic contractions of skeletal muscles mechanically compress the veins, reducing venous capacitance within the muscle bed and significantly increasing venous return.

DISCUSSION

The analyzed scientific literature indicates that explaining hemodynamic processes through a single physical law is insufficient. The circulatory system is a complex, multifactorial, and dynamic biological system in which pressure, flow velocity, vascular resistance, blood viscosity, vascular elasticity, and myocardial contractility interact closely. Therefore, the Bernoulli principle, Poiseuille law, Reynolds number, Frank–Starling law, Laplace law, and the continuity equation should be considered complementary theoretical frameworks for a comprehensive assessment of hemodynamics.

In the approach proposed by **Guyton and Hall**, cardiac output, venous return, arterial pressure, and systemic vascular resistance are emphasized as the central determinants of circulatory function. This concept is particularly important from the perspective of clinical physiology and has practical relevance in understanding conditions such as shock, heart failure, hypertension, and hypovolemia. This viewpoint is closely associated with Poiseuille's law, as changes in vascular radius and blood viscosity exert a profound influence on peripheral vascular resistance.

Studies by **Nichols and O'Rourke** as well as **McDonald** on arterial hemodynamics highlight that blood flow should not be evaluated solely in terms of static pressure and resistance. Instead, pulsatile flow, arterial elasticity, wave propagation, and the mechanical properties of the vascular wall must also be taken into consideration. This perspective is closely related to Laplace's law and the concept of vascular wall tension. In particular, the relationship among wall tension, vessel radius, and pressure is of considerable clinical importance in conditions such as arterial hypertension, aortic aneurysm, and left ventricular hypertrophy.

Among the physical principles applied in clinical practice, the **Bernoulli principle** is one of the most widely utilized, especially in Doppler echocardiography. The modified Bernoulli equation enables non-invasive estimation of pressure gradients across stenotic or regurgitant heart valves. In this regard, the Bernoulli principle represents one of the most practical and efficient biophysical models in cardiovascular diagnostics. Nevertheless, several authors have emphasized that this equation is based on a simplified model and does not fully account for factors such as blood viscosity, turbulence, vascular geometry, and energy dissipation that occur under physiological conditions.

The **Poiseuille law** is considered one of the fundamental principles for understanding vascular resistance. The fourth-power dependence of flow on vessel radius explains why even minor changes in arteriolar diameter can produce substantial effects on blood flow and arterial pressure.

Clinically, this law is highly relevant for interpreting hypertension, vasoconstriction, vasodilation, shock states, polycythemia, and anemia. However, because Poiseuille's law is derived under idealized conditions, its application to the real circulatory system is subject to limitations. Blood behaves as a non-Newtonian fluid, blood vessels are elastic, and flow is inherently pulsatile.

The **Reynolds number** serves as an important criterion for distinguishing between laminar and turbulent blood flow. Clinically, it is particularly useful for explaining flow disturbances associated with vascular stenosis, valvular narrowing, and the generation of cardiovascular sounds detected during auscultation. Turbulent flow increases energy loss, alters perfusion pressure, and imposes an additional workload on the cardiovascular system. Consequently, although the Reynolds number is mathematically simple, it plays a significant role in the interpretation of heart murmurs, Korotkoff sounds, and hemodynamic consequences of stenotic lesions.

The **Frank–Starling law** explains the intrinsic autoregulatory mechanism of cardiac function. This principle is essential for understanding the relationship among venous return, preload, stroke volume, and cardiac output. In clinical practice, it is widely applied in the assessment of fluid therapy, heart failure, hypervolemia, and hypovolemia. However, in advanced stages of heart failure, the compensatory capacity of the Frank–Starling mechanism becomes limited, necessitating cautious interpretation of this relationship in pathological conditions

Discussion (continued)

One of the major limitations of classical physical laws is that they are derived under idealized conditions. In the living organism, however, blood viscosity is variable, blood vessels are elastic, flow is pulsatile, vascular geometry is complex, and hemodynamic parameters are continuously influenced by neural and humoral regulatory mechanisms. Consequently, the Bernoulli principle, Poiseuille law, and Reynolds number are applied in clinical practice as simplified models. In certain situations, this may result in inaccuracies in the estimation of pressure gradients, flow velocity, or vascular resistance.

Future developments in hemodynamic assessment are expected to focus on the integration of classical physical principles with modern digital technologies, computational modeling, artificial intelligence, Doppler-based diagnostics, biosensor monitoring, and computational fluid dynamics (CFD). Such an approach may facilitate the identification of individual blood flow characteristics, enable earlier diagnosis of cardiovascular diseases, improve prediction of treatment outcomes, and expand the possibilities of personalized medicine.

Overall, the biophysical principles of hemodynamics provide an essential theoretical framework for understanding cardiovascular function, interpreting clinical manifestations, and accurately evaluating the results of modern diagnostic techniques. A comprehensive study of these principles strengthens the integration of medical education, clinical practice, and scientific research.

CONCLUSIONS

1. Hemodynamic processes are governed by the physical laws of blood flow, and the Bernoulli principle, Poiseuille law, Reynolds number, Frank–Starling law, and Laplace law constitute fundamental theoretical frameworks for explaining both normal and pathological cardiovascular function. These principles provide a scientific basis for understanding the relationships among blood flow, pressure, vascular resistance, and cardiac performance.

2. The Bernoulli principle and the continuity equation form the theoretical foundation of modern Doppler echocardiography and functional diagnostic techniques, enabling non-invasive assessment of valvular heart disease, vascular stenosis, and pressure gradients. Therefore, they represent some of the most widely applied hemodynamic models in clinical practice.

3. Poiseuille's law plays a crucial role in explaining the mechanisms underlying vascular resistance by demonstrating how changes in vessel radius, blood viscosity, and hematocrit significantly influence arterial pressure and tissue perfusion. This principle is particularly important for understanding the pathophysiology of hypertension, polycythemia, anemia, and shock.

4. The Reynolds number, Frank–Starling law, and Laplace law provide valuable insights into blood flow characteristics, the compensatory capacity of the heart, and the distribution of mechanical forces within vascular and ventricular walls. These principles have important clinical relevance in understanding the pathogenesis of heart failure, valvular disorders, arterial hypertension, aneurysms, and dilated cardiomyopathy.

5. Although classical physical laws are based on idealized models, their integration with modern diagnostic technologies, computational modeling, biosensor monitoring, and artificial intelligence systems offers new opportunities for more accurate hemodynamic assessment, early diagnosis of cardiovascular diseases, and the advancement of personalized medicine.

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