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EXPERT OPINION
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Haemodynamics of atherosclerosis: a matter of higher hydrostatic pressure or lower shear stress?

Xinggang Wang [1,2] and Junbo Ge [1]*

[1]Department of Cardiology, Zhongshan Hospital, Fudan University. Shanghai Institute of Cardiovascular Diseases, 180 Fenglin Road, Shanghai 200032, China; and [2]Institute of Biomedical Sciences, Fudan University, Shanghai, China

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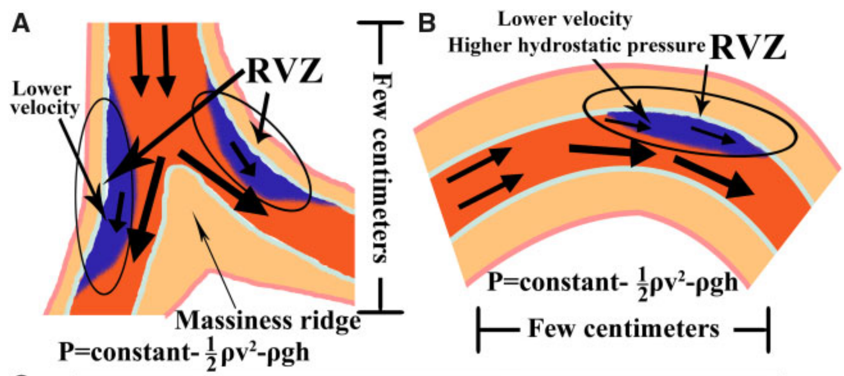
Atherosclerosis is prone to large and medium arteries which must bear much higher mechanical force, mainly hydrostatic pressure, shear stress, and tensile stretch. In general, with gradual increase of branches and total sectional area, velocity and pressure of blood will gradually decrease from aorta to capillaries. However, local velocity and pressure of blood might also be different even in the same transection of artery for variations of vessel structure and location. Blood belongs to viscous fluid with certain viscosity in the body. In the large and medium arteries, blood velocity is so fast that viscoelasticity could be negligible. Therefore, the Bernoulli's equation could be applied to these arteries: $P + \frac{1}{2}\rho v^2 + \rho gh$ = constant or P = constant - $\frac{1}{2}\rho v^2$ - ρgh (P: hydrostatic pressure, ρ: fluid density, v: blood velocity, g: gravitational acceleration, h: height). ρ and g are constants in an individual. The essence of Bernoulli's equation is energy conservation. At any point of per unit mass of fluid micro cluster, the sum of P, $\frac{1}{2}\rho v^2$ and ρgh is a constant. Even if the viscosity of blood is considered, the energy loss of blood flow should be very small over a very short distance (few centimetres, *Figure 1*). In addition, the energy loss of blood flow in the same transection is also very small due to the small diameter of blood vessel. At the same timepoint in a cardiac cycle, the constants (sums of P, $\frac{1}{2}\rho v^2$ and ρgh) of unit mass of fluid micro cluster are basically equal in a very short distance or in the same transection of artery, and Bernoulli's equation is still applicable here. At any point of per unit mass of fluid micro cluster here, the reduction of $\frac{1}{2}\rho v^2$ would be converted into P ($\Delta P = \frac{1}{2}\rho\ (\Delta v)^2$). Therefore, P is negatively related to v^2 in a very short distance or in the same transection of the artery (*Figure 1*). Since the direction of $\frac{1}{2}\rho v^2$ is parallel to the tangent direction of the vessel and the perpendicular force to the wall from $\frac{1}{2}\rho v^2$ at the tangent point is zero, $\frac{1}{2}\rho v^2$ has little effect on the vessel wall unless it is converted into P when the blood flow meets a curved or bifurcated vessel.

Different vessels have different susceptibility of atherosclerosis, and even in the same transection of the same artery, the susceptibility is different in different locations which is called eccentric lesions. Therefore, it is thought that this should be closely related to hemodynamics. We all know that the outer walls of bifurcations and the convex surface of curved arteries are usually the 'Relatively Vulnerable Zones' (RVZ) where atherosclerosis is often more serious compared with their neighbourhoods. For decades, many studies have confirmed that the areas of the outer walls of bifurcations have much lower blood velocity than their neighbourhoods.[1] Therefore, 'lower shear stress' is considered as a risk factor of atherosclerosis for decades. How does a lower shear stress, which has a much lower order of magnitude compared with hydrostatic pressure, damage the vessel or aggravate atherosclerosis? It is a puzzling question. Furthermore, shear stress of veins is similar to that of RVZ of arteries,[1] while intimal thickening of veins is not obvious as the arteries. There are many places in arterioles with lower shear stress as the decrease of blood velocity, while the thickening of arterioles is not as obvious as that of the medium-sized arteries. These issues make it unconvincing for us to explain atherogenesis with 'lower shear stress'.

When blood micro cluster flows over a very short distance or the same transection of the artery, previous studies did not consider the energy conversion between $\frac{1}{2}\rho v^2$ and P ($\Delta P = \frac{1}{2}\rho\ (\Delta v)^2$). Of course, we did not mean to deny the previous studies, while these studies are very meaningful and made us to further consider its essence. RVZ are places where blood velocity is lower than their neighbourhoods. According to Bernoulli's equation ($P + \frac{1}{2}\rho v^2 + \rho gh$ = constant), RVZ have much higher hydrostatic pressure than their neighbourhoods. It is well known that hypertension with higher hydrostatic pressure is the most common risk factor of atherosclerosis. This perfectly explains the predisposing sites of atherosclerosis, such as bifurcations and curved arteries (*Figure 1*). Therefore, 'low shear stress' aggravates atherosclerosis is an appearance, and the essence is that these areas with lower blood velocity have much higher hydrostatic pressure, which aggravates atherosclerosis.

This article involved many common knowledges of fluid physics, such as fluid mechanics, varied flow, the law of energy conservation, calculus, etc. For the convenience of understanding, we simplified some contents, which does not affect the conclusion. In fact, large numbers of fluid physics experiments have clearly verified these phenomena in both ideal and viscous fluids, and it is the common sense of fluid physics and widely used this phenomenon in industry. In short, RVZ of vessels bears higher mechanical force, which mainly comes from higher hydrostatic pressure

* Corresponding author. Tel: +86-21-64041990(2745), E-mail: jbge@zs-hospital.sh.cn



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Abbreviation	Pressure name	Energy name (Unit mass)
P	Hydrostatic pressure	Pressure potential energy
$\frac{1}{2}\rho v^2$	Dynamic pressure	Kinetic energy
ρgh	Gravitational potential pressure	Gravitational potential energy

Figure 1 Bernoulli's equation in atherosclerosis. (*A*) It is the illustration of bifurcations where and why atherosclerosis is prone to occur. Blood velocity near the outer walls of bifurcations is much lower than their counterparts in the same transection. With P = constant - $\frac{1}{2}\rho v^2$ - ρgh, these zones have much higher hydrostatic pressure (*P*) near the outer walls of bifurcations than their counterparts. This leads to more severe lesions in these 'Relatively Vulnerable Zones' (RVZ). (*B*) Large numbers of fluid physics experiments have verified these phenomena, and it is the common sense of fluid physics about varied flow. It is the illustration of curved artery where and why atherosclerosis is prone to occur. Blood velocity near the convex surface of curved arteries is lower than that of their neighbourhoods by common knowledge of fluid physics about varied flow. With P = constant - $\frac{1}{2}\rho v^2$ - ρgh, these zones have much higher hydrostatic pressure (P) near the convex surface of curved arteries compared with their neighbourhoods. (*C*) Different names of parameters in Bernoulli's equation.

of blood flow. In addition, basing on the energy conversion between $\frac{1}{2}\rho v^2$ and P of fluids, local velocity (v), and local hydrostatic pressure (P) of blood flow would be variable in the neighbourhoods even in the same transection of arteries for sudden bending or bifurcations of vessels. This provides a basis for us to understand the variation characteristics of local hydrostatic pressure (P) and local blood flow velocity (v) more comprehensively.

Conflict of interest: none declared.

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

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Authors

Biography: Xinggang Wang received a doctor's degree in cardiovascular medicine at Zhongshan Hospital Fudan University at 2014 and mainly engaged in the immune-related research of cardiovascular diseases. From 2014 to 2017, he served as a resident and attending physician of Department of Cardiology in the First Affiliated Hospital of Soochow University. Since 2017, as a postdoctoral of Professor Junbo Ge in Fudan University, he has been engaged in the research on the pathogenesis of atherosclerosis.

Biography: Junbo Ge is FACC, FESC and Academician of the Chinese Academy of Sciences. Prof. Ge has been engaged in the clinical work and scientific research of cardiology since 1987. Dedicated to the optimization and innovation of diagnosis and treatment strategy for coronary artery disease and made extraordinary achievements in intravascular ultrasound (IVUS). Research fields also include development of novel coronary stents and treatment strategy optimization of complex CAD. He is the Chairman of Chinese Cardiovascular Association, Director of Department of Cardiology/Catheter Lab in Zhongshan Hospital Fudan University, Director of Shanghai Clinical Medical Center for Cardiovascular, Chairman of Shanghai Institute of Cardiovascular Diseases, Head of Institutes of Biomedical Sciences of Fudan University, Head of Institute of Panvascular Medicine of Fudan University, Director-General of Fudan University Panvascular Foundation, Director of Engineering Research Center for Cardiovascular Devices of Ministry of Education of the People's Republic of China, Board of Trustee in Society for Cardiovascular Angiography and Interventions, International Advisor of American College of Cardiology International Council.