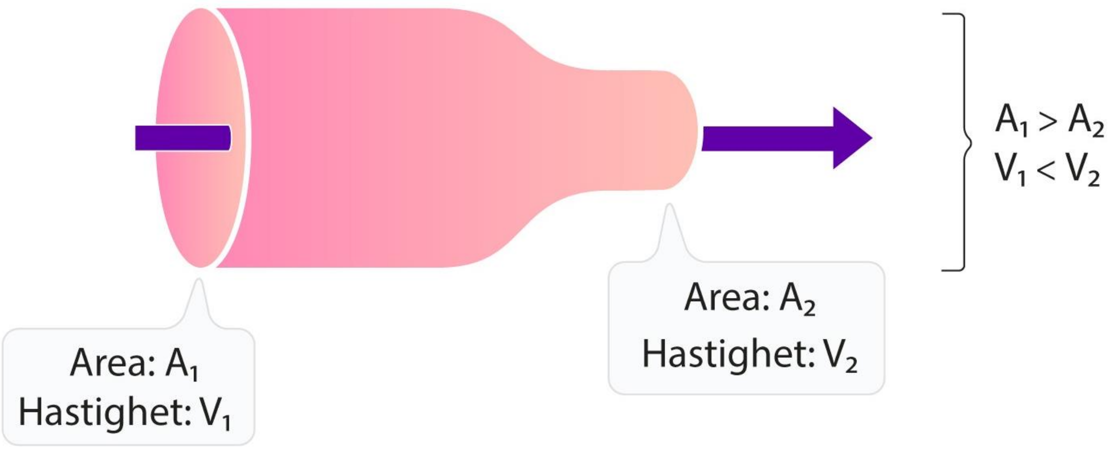
Continuity Equation

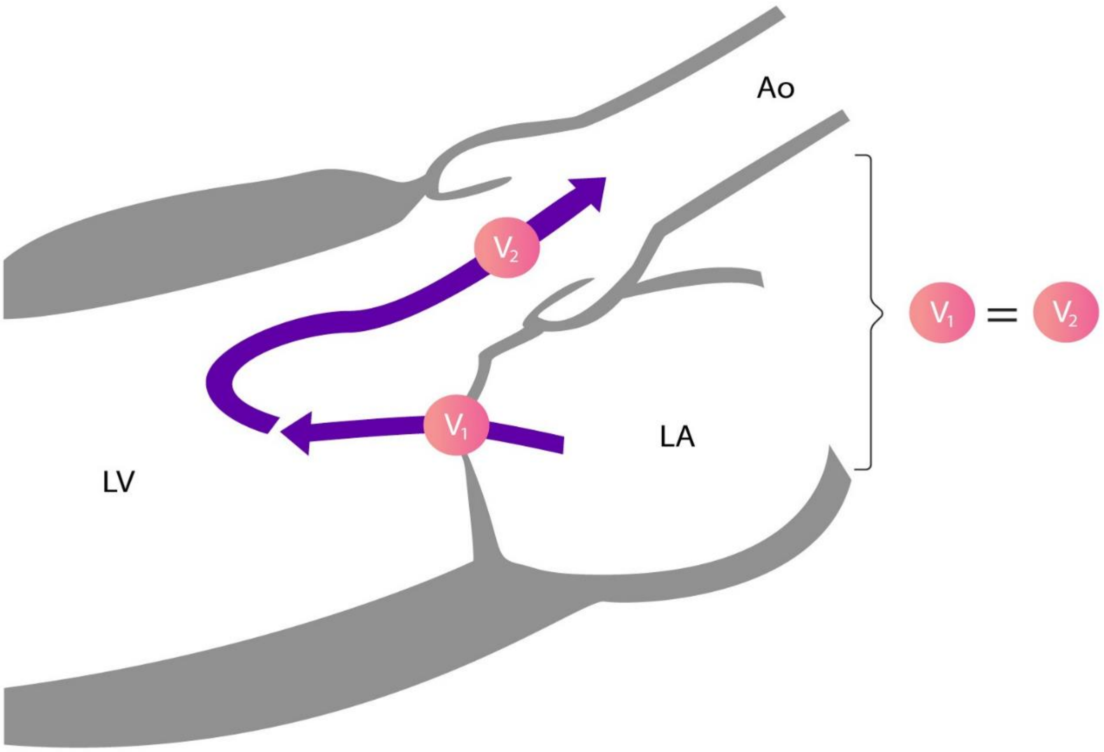
The *principle of continuity (the continuity equation)*, which states that the volume of blood flowing into a chamber must be equal to the volume flowing out of the same chamber.

Thus, the blood volume flowing through the mitral valve in diastole is equal to the volume flowing through the aortic valve during systole.

The velocity of blood is inversely related to the area of the orifice; velocity increases with diminishing area of the orifice, and vice versa.

$$A_1 \cdot V_1 = A_2 \cdot V_2$$





Grading of the severity of stenoses using the continuity equation

All valvular stenoses must be graded in order to optimize management according to disease severity. The most important parameter, for grading of stenoses, is the opening area of the stenosis. The smaller the area, the more pronounced the stenosis and, accordingly, the greater the hemodynamic effect. The continuity equation can be used to calculate the area of the valve. The following formula indicates that flow over the mitral valve is equivalent to flow over the aortic valve:

$$\mathbf{area_{mitralis} \cdot VTI_{mitralis} = area_{aorta} \cdot VTI_{aorta}}$$

Usefulness of the Continuity Equation in Echocardiography:

- **Assessing Valve Stenosis:** The continuity equation is widely used in echocardiography to assess the severity of valve stenosis, particularly aortic stenosis. By comparing the flow velocities and cross-sectional areas, it helps calculate the valve area, which is crucial for diagnosis and treatment decisions.
- **Non-invasive Estimation of Cardiac Output:** It provides a non-invasive way to estimate cardiac output by measuring the blood flow through different parts of the heart, such as the aortic or pulmonary valves. This is especially useful in patients where invasive procedures may be risky.
- **Quantifying Regurgitant Volume:** In the case of valvular regurgitation, the continuity equation helps estimate the volume of blood that leaks backward through a valve. This aids in assessing the severity of regurgitation, which is critical for deciding whether surgery is needed.
- **Evaluating Prosthetic Valves:** The continuity equation can be used to evaluate the function of prosthetic valves by comparing the effective orifice area before and after valve replacement. This helps in monitoring post-surgical outcomes.

Limitations of the Continuity Equation in Echocardiography:

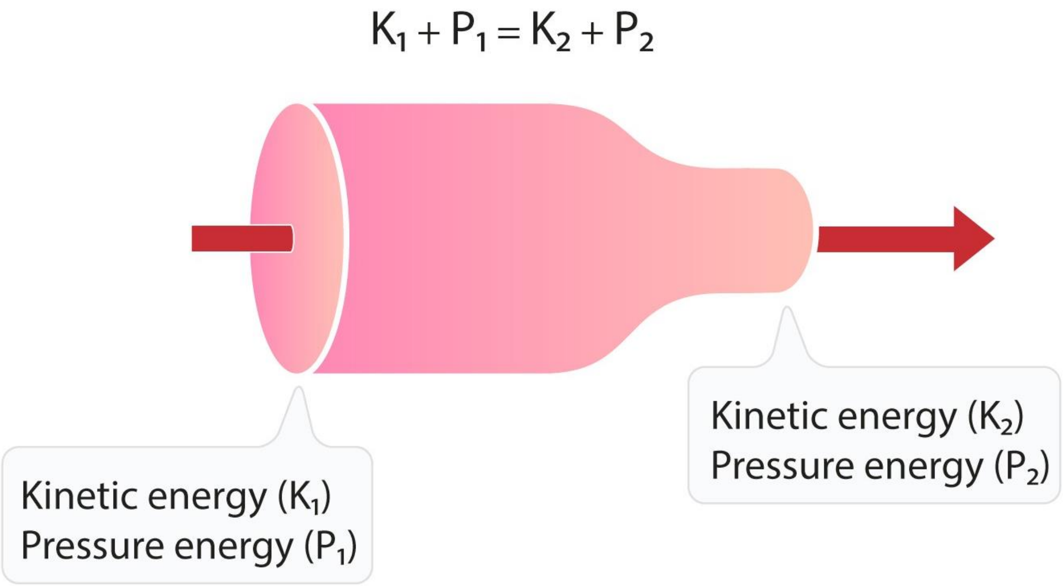
- **Assumes Circular Orifices:** The equation assumes that the flow occurs through circular orifices. However, many heart valves and pathological orifices are not perfectly circular, which can lead to inaccuracies in the calculated valve area.
- **Requires Accurate Measurements:** The accuracy of the continuity equation depends on precise measurements of velocity and cross-sectional area. In echocardiography, obtaining these measurements can be challenging due to suboptimal imaging windows or poor image quality, leading to potential errors in the results.
- **Neglects Valve Geometry and Flow Eccentricity:** The continuity equation doesn't account for the complex geometry of valves or eccentric flow

patterns, which can occur, for example, in aortic stenosis with calcified valves. These factors may reduce the accuracy of the calculation.

- **Limited by Inconsistent Flow Assumptions:** It assumes laminar, steady flow, which is often not the case in pathological conditions, such as turbulent flow through stenotic valves. This can result in underestimation or overestimation of valve areas or regurgitant volumes.
- **Influenced by Heart Rate and Stroke Volume Variability:** Variability in stroke volume or heart rate, as seen in patients with arrhythmias like atrial fibrillation, can make it difficult to apply the continuity equation consistently, leading to fluctuating or unreliable results.
- **Not Applicable in Certain Pathologies:** The continuity equation may not provide useful information in cases where there are multiple simultaneous valvular lesions (e.g., combined stenosis and regurgitation), as the complex interactions can distort the assumptions required for its use.

Bernoulli

The Bernoulli principle is based on the *law of conservation of energy*, which states that the total energy of an isolated system remains constant over time; energy can neither be created nor destroyed, it can only be transformed or transferred from one form to another. Blood flowing through the heart and vessels obey the law of conservation of energy. It follows that the sum of kinetic energy (K) and pressure energy (P) of blood must be equal in two separate points in the system



According to the Bernoulli principle, the sum of kinetic energy (K) and pressure energy (P) is constant as blood flows through the circulatory system. The equality of kinetic and pressure energy at two separate points can be formulated as follows:

***Formula 1*:**

$$P_1 + K_1 = P_2 + K_2$$

Kinetic energy (K) is a function of velocity (v) and density (D) of the liquid:

***Formula 2*:**

$$K = 0.5 \cdot D_{blood} \cdot v^2$$

With regards to echocardiography and ultrasound imaging in general, v is the maximum velocity measured using Doppler. Moreover, the first part of the formula ($0.5 \cdot D_{blood}$) can be approximated to 4, meaning that *Formula 2* can be rewritten as follows:

***Formula 3*:**

$$K = 4v^2$$

Formula 1 can be rewritten as follows:

Formula 4:

$$P_1 + 4v_1^2 = P_2 + 4v_2^2$$

The pressure difference will then be:

Formula 5:

$$P_1 - P_2 = 4v_2^2 - 4v_1^2$$

Which can be rewritten:

Formula 6:

$$\Delta P = 4(v_2^2 - v_1^2)$$

This formula is excellent for measuring pressure gradients across small openings, such as the valves. Importantly, in the setting of valvular stenosis or regurgitation, the proximal velocity (v_1) is very small compared to the distal velocity (v_2), and the difference becomes even greater after squaring the velocities. Thus, v_1 can be ignored, which results in the **simplified Bernoulli equation**:

Formula 7:

$$\Delta P = 4v_2^2$$

This equation is also referred to as the *modified Bernoulli equation*. ΔP is the pressure gradient (mmHg) across a valve.

The Bernoulli principle can be used to calculate pressure gradients across valvular stenoses and regurgitations. The equation is agnostic to the direction of the blood flow; it merely measures the pressure gradient across a small orifice. According to the Bernoulli principle, the flow through the orifice will depend on the pressure gradient across it.

Example 1: A maximum velocity of 4 m/s is measured across the aortic valve. The pressure gradient equals:

$\mathbf{4 \cdot 4^2 = 64}$ **mmHg**

The pressure gradient between the left ventricle and the aorta is 64 mmHg.

Example 2: A maximum velocity of 3 m/s is measured across the tricuspid valve. The pressure gradient equals:

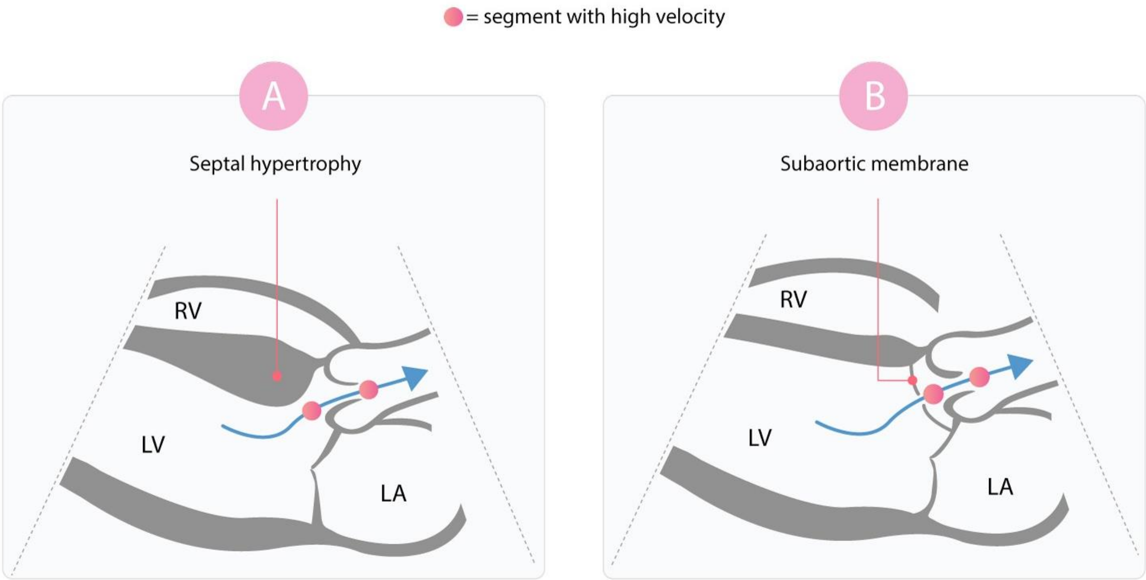
$\mathbf{4 \cdot 3^2 = 36}$ **mmHg**.

The pressure gradient between the right ventricle and the right atrium is 36 mmHg.

Disadvantages of the Bernoulli equation

The Bernoulli equation is highly dependent on the precision of the Doppler measurement. The Doppler beam must be parallel to the direction of the blood flow (refer to The Doppler Equation). Any angle error between the Doppler beam and the blood flow will result in an underestimation of the velocity. In clinical practice, angle errors less than 15˚ are acceptable (cos 15˚ = 0.97). Velocity at v_2 will be miscalculated by approximately 6% at an angle error of 15˚

There are situations where v_1 (proximal velocity) cannot be ignored. The most common situation is when assessing aortic stenosis in the presence of a narrowing of the LVOT (left ventricular outflow tract). Such narrowing is due to septal hypertrophy or subaortic membrane



(A) Septal hypertrophy and (B) subaortic membrane. LVOT is narrowed in (A) and (B).