Blood Flow Measurements

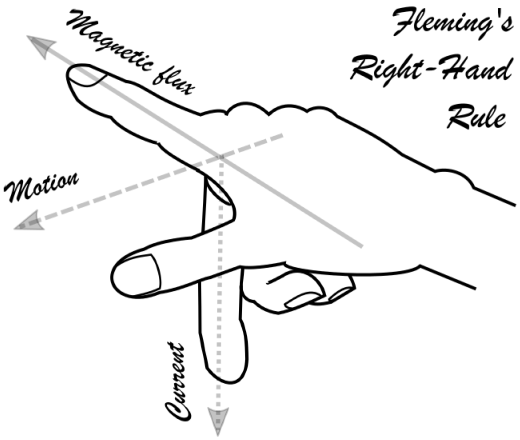
BME 362 Lecture Notes *Ying Sun*

Instantaneous flow measurement: 1) Electromagnetic flowmeter
2) Ultrasonic flowmeter

Mean flow measurement: 1) Indicator dilution method
2) Fick's method

Electromagnetic flowmeter (pp. 338-344 textbook)

An induced current is generated when a conductor moves in a magnetic field. As shown in the figure, Fleming's right-hand rule defines which direction the current flows. The right hand is held with the thumb, index finger and middle finger mutually perpendicular to each other. The thumb is pointed in the direction of the motion of the conductor. The index finger is pointed in the direction of the magnetic field (north to south). The middle finger represents the direction of the induced or generated current within the conductor (from the negative terminal to the positive terminal, like a battery). Noticed that Fleming's right-hand rule applies to an electric generator that produces a current. For an electric motor that requires an external current supply, Fleming's left-hand rule applies.

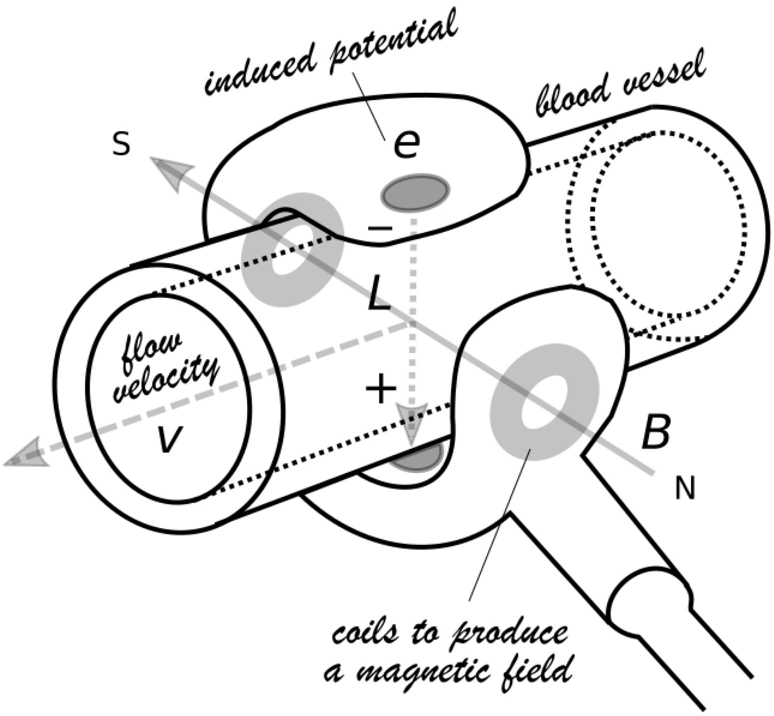


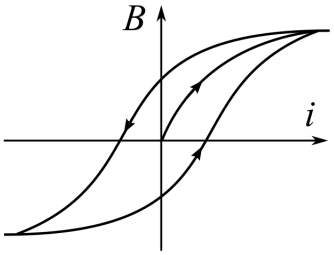
The electromagnetic flowmeter uses a probe that cuffs around a blood vessel. As shown in the figure, the probe contains magnetic coils to produce a magnetic field B. Two electrodes are arranged in a direction perpendicular to the direction of the magnetic field to pick up the induced potential e, as blood moves through the blood vessel at a flow velocity v.

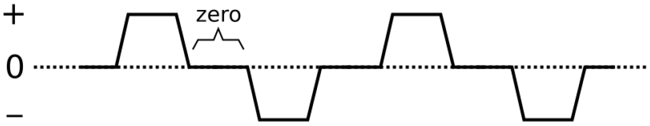
$$e = BLv,$$

where L is the distance between the two electrode.

For DC excitation, the magnetic field B is constant. Because the induced voltage e does change its polarity, caution must be taken against chemical burns. Chemical burns can occur even with a small DC voltage over a prolonged period of time.

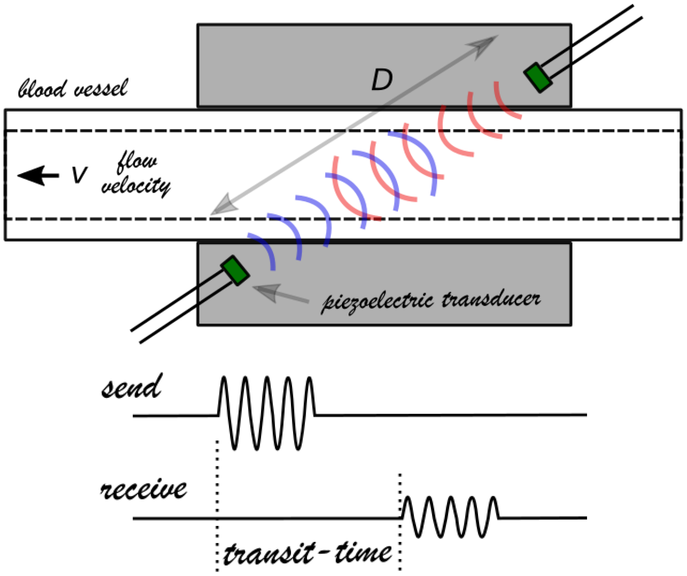






For AC excitation, the magnetic field B keeps changing its polarity. The induced voltage e also changes its polarity. The lack of a DC component has the advantage of avoiding the risk of chemical burns. However, the magnetic hysteresis needs to be taken into account. Magnetic hysteresis is the irreversibility of the magnetization and demagnetization process. As shown in the figure, the magnetic field (B) follows different curves as the current (i) producing the magnetic field increases and decreases. The current excitation usually follows a return-to-zero waveform as shown. The zero portion can be used to calibrate the instrument by providing baseline for the zero-flow reference. Based on the previous equation, the effect of $B = 0$ should be the same as that of $v = 0$. The direct voltage output (e) of the electromagnetic flow probe is proportional to some average value of the flow velocity (v). For laminar flows through a circular pipe, the velocity profile is a parabola. The volume flow rate is the integration of the velocities over the cross-section of the lumen of the blood vessel, which can be approximated by the average flow velocity times the cross-sectional area. Because the cross-sectional area inside the flow probe does not change, instantaneous volume flow rate can be measured. However, a calibration process is required that involves the measurement of blood volume through the flow probe at a constant flow rate during a known period of time.

Ultrasonic flowmeter (pp. 344-355 textbook)



The instantaneous flow waveform can also be measured by use of an ultrasonic flowmeter. The instrumentation is based on the transit-time difference of the ultrasound traveling upstream versus downstream. The piezoelectric transducer serves as a sound transmitter as well as a receiver. As shown in the figure, a pair of ultrasonic transducers are positioned diagonally across the blood vessel. The transit-time between the two transducers is measured upstream and downstream in an alternating fashion. The transit-time is measured by sending a burst of ultrasound wave from one transducer and receiving the burst of wave with the opposing transducer. The downstream transit-time is shorter than the upstream transit-time. Let the velocity of the ultrasound be u and the blood flow velocity v. The distance between the two transducers is D. The upstream and downstream transit-times are given by:

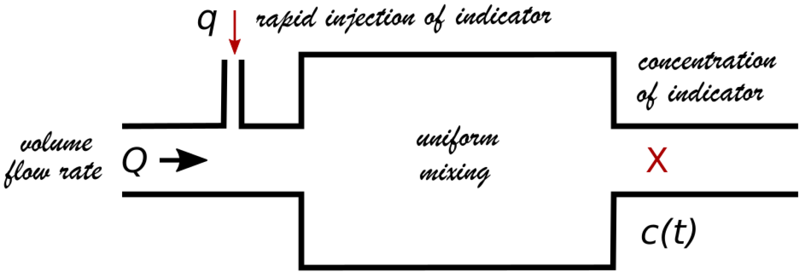
$$T_{up} = \frac{D}{u-v}, \quad T_{dn} = \frac{D}{u+v}.$$

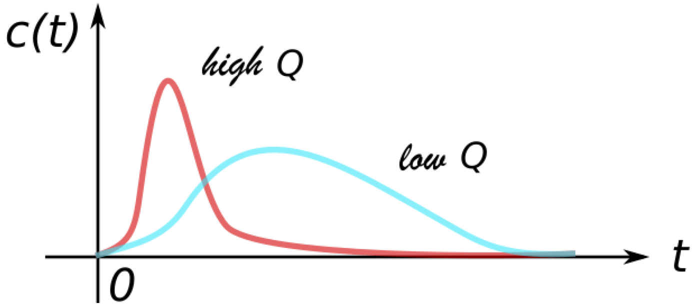
Solving for v, we have

$$v = \frac{D}{2}\left(\frac{1}{T_{dn}} - \frac{1}{T_{up}}\right)$$

Same as the electromagnetic flowmeter, the direction output of the ultrasonic flowmeter is an average value of the blood flow velocity. A calibration process is needed to provide the volume flow rate.

Indicator Dilution Method (pp. 332-335 textbook)





As shown in the figure, a bolus of an indicator (q) is quickly injected at the inflow of a chamber. The indicator mixes into the blood flow (Q) and its concentration *c(t)* is measured at the outflow. The concentration of the indicator at the outflow increases initially and then is washed out. As shown in the figure, the concentration curve depends on the flow rate Q. The amount of indicator is the time integration of the flow times the concentration:

$$q = \int_0^\infty Q \cdot c(t)\,dt$$

If Q is a constant, we have

$$q = Q \int_0^\infty c(t)\,dt$$

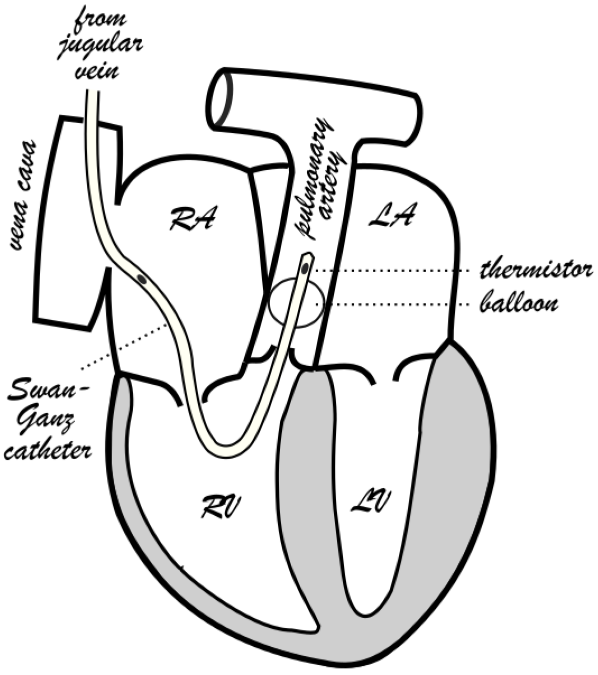
or $$Q = \frac{q}{\int_0^\infty c(t)\,dt}$$. The flow is inversely proportional to the area under the concentration curve.

This deviation is based on the following assumptions:

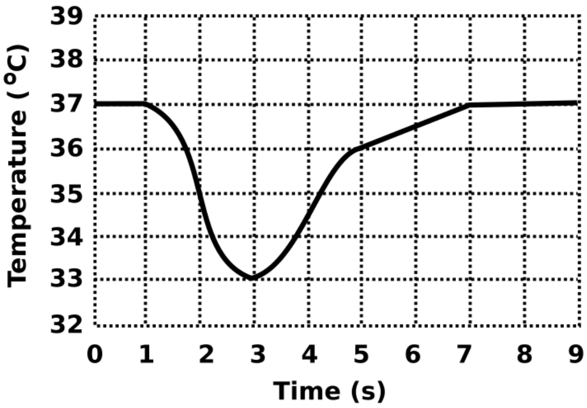
- Rapid injection
- Fixed volume system
- Constant flow rate
- Instantaneous and uniform mixing
- No recirculation

Thermodilution is an indication dilution method for measuring the cardiac output by using *heat* as the indicator. This is accomplished by using a special catheter called Swan-Ganz catheter as shown. The catheter is inserted, with the balloon deflated through the jugular vein, right atrium, tricuspid valve. Once the tip of the catheter is in the right ventricle, the balloon is inflated. The blood flow carried the balloon – like a sail – through the pulmonary valve. The tip of the catheter is finally positioned in the pulmonary artery.

A bolus of iced or room-temperature saline is injected through a side hole of the catheter in the right atrium. Thus, the indicator is heat (negative heat to be precise). The temperature is measured by a thermistor at the tip of the catheter.



Consider the following example: The cardiac output is determined by use of the thermodilution method. A bolus of 24 ml iced saline (0 °C) was rapidly injected into the right atrium. The temperature is measured in the pulmonary artery as shown on the right. Assume a heat loss factor of 0.85. Determine the cardiac output in terms of liters per minute.



The flow is determined by:

$$Q = \frac{K \cdot q}{\int_0^{\infty} c(t)\,dt}$$

where K is the heat loss factor. The unit for the indictor (heat) is calorie. One calorie is the energy needed to raise the temperature of 1 gram of water through 1 °C (now usually defined as 4.1868 joules). The specific heat of saline is about the same as that of water, or 1 $\mathrm{cal}/(\mathrm{ml}\cdot{}^{o}\mathrm{C})$. The amount of indicator is:

$$q = 24\,\mathrm{ml}\cdot(37^{o}\mathrm{C} - 0^{o}\mathrm{C})\cdot(1\,\mathrm{cal}/(\mathrm{ml}\cdot{}^{o}\mathrm{C})) = 888\ \mathrm{cal}$$

$\int_0^{\infty} c(t)\,dt$ can be calculated by counting the blocks enclosed by the curve, which is $10\ \mathrm{s}\cdot{}^{o}\mathrm{C}$.

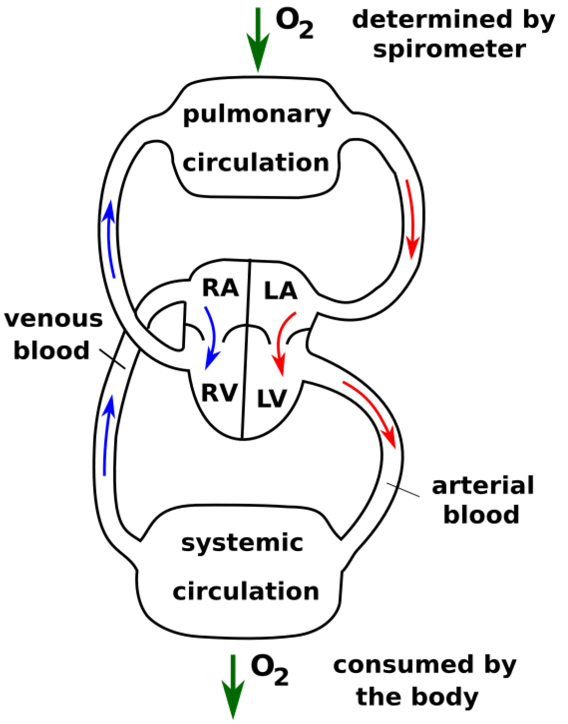
Thus, we have

$$Q = \frac{K \cdot q}{\int_0^{\infty} c(t)\,dt} = \frac{(0.85)(888\,\mathrm{cal})}{(10\,\mathrm{s}\cdot{}^{o}\mathrm{C})\cdot(1\,\mathrm{cal}/(\mathrm{ml}\cdot{}^{o}\mathrm{C}))} = 75.5\,\mathrm{ml}/s = 75.5\times 60/1000\ \mathrm{l/min} = 4.5\ \mathrm{l/min}$$

Fick's Method (pp. 332-335 textbook)

In 1870, Adolf Fick suggested that the total uptake or release of a substance (dm/dt) to an organ is the product of the blood flow (Q) and the arteriovenous concentration difference, $C_a - C_v$, of the substance. Thus, the blood flow can be calculated according to:

$$Q = \frac{dm/dt}{C_a - C_v}$$



Example

As shown in the figure, the oxygen consumption measured by using a spirometer is 300 ml/min. The oxygen concentration measured by using a blood gas machine is 0.24 ml/ml in the arterial blood and 0.18 ml/ml in the venous blood. Determine the cardiac output in terms of liter/min.

$$Q = \frac{300\ \mathrm{ml/min}}{(0.24 - 0.18)\,\mathrm{ml/ml}} = 5000\ \mathrm{ml/min} = 5\ \mathrm{l/min}$$