5. Direct Flow

- Hemodynamic properties
- Electromagnetic flowmeter
- Ultrasonic flowmeter
  - Transit-time flowmeter
  - Ultrasonic Doppler flowmeter
- Laser Doppler flowmeter
- Dilution method
- Thermal flowmeter
- Red blood cell speedometer

Object Quantities

Amount of flow

- **Volume flow rate**
  - volume crosses a surface within a unit time
  - SI system $\rightarrow$ m$^3$/s
  - physiological measurement $\rightarrow$ L/s, L/min, mL/min
- **Mass flow rate**
  - mass crosses a surface within a unit time
  - kg/s

Blood Flow in Vessels

Flow rate and velocity vary in different size of blood vessels.

No one measurement method is available to the whole range of flow rates or velocity.

Blood Flow in Tissues

Tissue blood flow varies significantly for different tissues and physiological conditions.
Velocity Profile in a Vessel

Steady and laminar flow

a long straight tube having
a circular cross section

Velocity

\[ U(r) = U_m(1 - r^2/R^2) \]

Flow rate

\[ Q = \int_0^R U(r)2\pi dr = \frac{1}{2} \pi R^2 U_m \]

Backward flow

Pulsatile flow

large artery

Electromagnetic Flowmeter

Principle = when a fluid containing electric charges \( q \) flows in a magnetic field \( B \) with velocity \( U \), an electromotive force \( F \) will be exerted on the particle.

**Electromotive force**

\[ F = q(U \cdot B) \]

If the magnetic field and the velocity are uniform, then:

\[ V = d \cdot U \cdot B \]

\( V \): potential difference between two electrodes
\( d \): the distance between two electrodes
\( U \): flow velocity
\( B \): magnetic flux density

Three Types of Electromagnetic Flowmeter

A) Cannular:

vessel is cut transversely, and its ends are attached to the rigid inflow and outflow tubes of the probe.

B) Perivascular:

a rigid cuff that contains magnet and electrodes and can be slipped around the vessel.

C) Intravascular:

magnet coils and sensing electrodes are fitted to the tip of catheter, and the catheter is inserted into the vessel.

Cannular Electromagnetic Flowmeter Probe
**Ultrasonic Blood Flowmeter**

- A sound wave propagating in a moving medium is affected by the velocity of the medium
- Sound scattered by a moving object is affected by the velocity of the scattering object
- Both phenomena can be used to measure blood flow velocity or flow rate in a blood vessel
- **Transit time** flowmeter and **Doppler** flowmeter

**Propagation of Ultrasound**

- Ultrasound frequency $> 20$kHz $c = f\lambda$
- Sound velocity $c$, frequency $f$ and wave length $\lambda$
- When sound **pressure** $p$ and sound particle **velocity** $U$ (or medium velocity), **characteristic impedance** becomes $Z=p/U=pc$ ($\rho$ medium density)
- Sound wave will be **partially reflected** by different **characteristic impedance** on boundary between two different media

\[
P_r = \frac{Z_1 - Z_2}{Z_1 + Z_2} P_i
\]

- Incident intensity of sound wave
- Reflection intensity of sound wave
Typical Values of Various Tissues

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Velocity (m/s)</th>
<th>Impedance ((10^4 \text{Pa} \cdot \text{s/m}))</th>
<th>Attenuation ((\text{dB/cm at 1 MHz}))</th>
<th>Half Value Layer at 1 MHz cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (STP)</td>
<td>330</td>
<td>0.0004</td>
<td>12</td>
<td>0.25</td>
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<tr>
<td>Water</td>
<td>1480</td>
<td>1.48</td>
<td>0.002</td>
<td>1500</td>
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<tr>
<td>Fat</td>
<td>1450</td>
<td>1.38</td>
<td>0.63</td>
<td>4.76</td>
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<tr>
<td>Blood</td>
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<td>1.61</td>
<td>0.18</td>
<td>16.67</td>
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<tr>
<td>Kidney</td>
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<td>1.62</td>
<td>1.0</td>
<td>3.00</td>
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<tr>
<td>Soft tissue</td>
<td>1540</td>
<td>1.63</td>
<td>0.70</td>
<td>4.29</td>
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<tr>
<td>Liver</td>
<td>1550</td>
<td>1.65</td>
<td>0.94</td>
<td>3.19</td>
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<tr>
<td>Muscle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aligned fiber</td>
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<td>1.3</td>
<td>2.31</td>
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<tr>
<td>Across fiber</td>
<td>—</td>
<td>—</td>
<td>3.3</td>
<td>0.91</td>
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<tr>
<td>Bone</td>
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<td>7.80</td>
<td>15</td>
<td>0.20</td>
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<tr>
<td>Ceramic crystal</td>
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<td>3.0</td>
<td>2.3</td>
<td>—</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>2670</td>
<td>3.2</td>
<td>2.3</td>
<td>—</td>
</tr>
</tbody>
</table>


Ultrasonic Transit Time Method

Transit Time

\[
T = \frac{D}{c \pm U \cos \theta}
\]

- \(D\): distance between transmitting and receiving elements
- \(U\): fluid velocity
- \(\theta\): beam angle with respect to the axis of the conduit
- \(c\): sound velocity
- \(\pm\): downstream (+) or upstream (-)

Difference in Transit Time

\[
\Delta T = \frac{2DU \cos \theta}{c^2 - U^2 \cos^2 \theta} \approx \frac{2DU \cos \theta}{c^2}
\]

Difference in Phase

\[
\Delta \phi = \omega \Delta T
\]

- \(\omega\): angular frequency of the sound wave

Wide-beam Technique

Ultrasonic beam is wider than the vessel diameter

\[
A = G \left[ S \cdot \sin \alpha \pm \frac{\omega Q \cdot \cos \alpha}{c^2} \cdot \cos \omega t \right]
\]

- \(A\): signal amplitude
- \(G\): coupling constant
- \(S\): crystal’s surface area
- \(\alpha\): beam angle
- \(Q\): total flow

Transit-time Ultrasonic Flowmeter

- bi-directional acoustic pathway
- acoustic reflector
- vessel 1 - 32 mm
- probe body
- cable
**Doppler Shift**

Doppler shift in the scattered wave due to the moving red blood cells in the blood stream:

\[ f_2 = \frac{c}{c-U \cos \varphi} f_1 \]

\[ f_1 = \frac{c+U \cos \theta}{c} f_s \]

\[ \Delta f = f_2 - f_s = \frac{c+U \cos \theta}{c-U \cos \varphi} f_s - f_s = \frac{U (\cos \theta + \cos \varphi)}{c} f_s \]

If \( \theta = \varphi \), \( \Delta f \approx \frac{2U \cos \theta}{c} f_s \) \( c >> U \cos \varphi \)

**Spectrum of Doppler Signal**

Normal femoral arterial flow

**Methods for Specific Site**

Range discriminating Doppler flowmeter aims to select special site

**Pulse Doppler Method**

By gating the received signal at a specific time interval, the signal reflected by the object in a specific range can be obtained selectively.
Random-signal Doppler System

The transmitted wave is modulated by a noise wave, and correlation is taken between the received wave and the delayed noise wave with a definite delay time.

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Among the received waves, only the reflected wave components from an object in a definite range, at which the transit time is just the delay time, can have a strong correlation.

Perivascular Doppler Flowmeter

Implantable use in experimental animals and clinical use during surgical operation.

Pulse Doppler Catheter

Wire leads Side hole Catheter body Epoxy Circular crystal

(a) 4.3 mm End hole

Pulse Doppler Catheter

Wire leads Internal sheath Catheter body Epoxy

Flexible steerable guide wire
**Indicator Dilution Method**

The process of making weaker or less concentrated indicators = color dyes, radio isotopes, electrolytes, or heat

Injecting indicator

录g, the concentration of indicator

upstream

downstream

amount of injected indicator

Mixing chamber

Recirculation

Concentration of the indicator at time $t$

$I = \int_{0}^{\infty} Q \cdot c(t) dt$

**Empirical Approximation of Initial Circulation Component**

Two-point method

Forward triangle method

Half width method

**Thermodilution Catheter**

Heat → temperature change

Cold fluid (saline or isotonic dextrose solution, 0°C, 10ml)

Swan-Gantz
Cardiac Output Monitoring

Continuous Thermodilution Catheter

Heat Dissipation Method

The rate of heat dissipation from a heated element placed in the blood stream depends on the flow velocity.

At a constant temperature operation

\[ H = RI^2 \]

\[ H = a + bU^m \]

\[ m \approx 0.5 \]

\( a \) and \( b \) are constants and determined by calibration, \( U \) is flow velocity.

Thermistor Velocity Probe

Two thermistors are commonly used in the flow probe. One measures the fluid temperature, and the other is heated to a higher temperature, and the temperature difference between the heated thermistor and the fluid is kept constant.

A fine wire for heating is wound around the sensing element.
Hot-film Velocity Probe

The thin metal film is maintained at a constant temperature of about 5°C above the flowing fluid temperature by employing the feedback bridge.

Red Blood Cell Velocity

\[ U = \frac{\delta}{t_m} \]

\( U \) = oxygen uptake

CO = \[ \frac{\int_0^T F_1 dt}{T} \] - \[ \frac{\int_0^T F_2 dt}{T} \] = \[ \frac{Q_T}{(c_2 - c_1)\tau} \]

\( Q_T \) = oxygen uptake

Balance for the volume of indicator

- Fick's principle

Blood ejected from RV travels along PA and in capillaries of the lungs uptakes oxygen from the alveoli, then through PV gets LA.
Red Blood Cell Velocity

\[ \varphi(\tau) = \int f_1(t) f_2(t + \tau) \, dt \]

the average transit time for a red blood cell to cross a fixed distance is obtained by seeking the maximum cross-correlation function.

\[ U = \frac{\delta}{t_m} \]

time interval is fixed, and the transit distance in this time interval is determined by searching maximum spatial cross correlation.

Mechanical Flowmeters

The flowing fluid has kinetic energy, and may cause a force or displacement in the sensing element when it is disturbed by a mechanical element, corresponding to the flow rate or flow velocity.

\[ \Delta P = \rho \delta \frac{dU(t)}{dt} + \alpha U(t) \]

When a red blood cell moves across the grating with a velocity \( U \), light signals have a frequency component of \( f = U/d \)

\[ F = 2QL \frac{d\theta}{dt} \]

Discrimination of flow direction