Lecture 10
Measuring Blood Pressure
This Week in PBS&D

HemoDynamics
- Blood vessels
- Pressure gradient
- Factors affecting blood pressure and homeostasis of blood pressure
- Shock
- Blood and its components

Measuring Blood Pressure and Sounds
- Direct measurement of BP
- Dynamic properties of the direct measurement catheter systems
- Heart sounds
- Indirect measurements of the BP
  - Auscultation and oscillometric methods
Blood transports $O_2$ and nutrients to tissues, and carry metabolic waste away from the cells.

The transportation is made possible by a “pressurized vessel” system, the arteries, veins, arterioles, venuoles and capillaries, 100,000 km in all...

The pressure is provided by a mechanical pump, the heart.

Measuring this pressure at various locations of this transportation network carries significant clinical information. These measurements can be made directly or indirectly.
BP In and Around the Heart

Arterial
SP = 90 - 150 mm Hg
DP = 60 - 80 mm Hg

Pulmonary artery
SP = 20 - 30 mm Hg
DP = 8 - 12 mm Hg
Wedge = 6 - 12 mm Hg

Right atrium
MP = 2 - 6 mm Hg

Left atrium
MP = 6 - 12 mm Hg

Left ventricle
SP = 90 - 150 mm Hg
DP = 6 - 12 mm Hg

Right ventricle
SP = 20 - 30 mm Hg
DP = 2 - 6 mm Hg
Blood Pressure Classification

Classification of blood pressure levels for adults 18 years and older. Systolic pressure, the higher number of a blood pressure reading, is the pressure as the heart pumps; diastolic pressure is the pressure when the heart relaxes between beats.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SYSTOLIC (mm Hg†)</th>
<th>DIASTOLIC (mm Hg†)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal*</td>
<td>&lt; 130</td>
<td>&lt; 85</td>
</tr>
<tr>
<td>High normal</td>
<td>130-139</td>
<td>85-89</td>
</tr>
<tr>
<td>Hypertension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STAGE 1 (Mild)</td>
<td>140-159</td>
<td>90-99</td>
</tr>
<tr>
<td>STAGE 2 (Moderate)</td>
<td>160-179</td>
<td>100-109</td>
</tr>
<tr>
<td>STAGE 3 (Severe)</td>
<td>180-209</td>
<td>110-119</td>
</tr>
<tr>
<td>STAGE 4 (Very Severe)</td>
<td>&gt;209</td>
<td>&gt;119</td>
</tr>
</tbody>
</table>

Optimal blood pressure is less than 120/80 mm Hg. Unusually low readings should be evaluated by a physician.
Invasive measurements – two major techniques:

- Couple vascular pressure to an external sensor via a liquid-filled catheter (extravascular pressure sensor)
- Place the sensor on the catheter tip which is directly inserted into the vessel of interest (intravascular pressure sensor).
Extravascular Sensors

Flush solution under pressure

Sensing port

Sample and transducer zero stopcock

Roller clamp

Disposable pressure transducer with an integral flush device

Electrical connector
Catheter connected to a pressure sensor through 3-way stopcock

System is filled with saline-heparin solution (anticoagulant agent), must be flushed every few minutes

Catheter inserted through surgical cut down or percutaneous insertion

BP info is transmitted via the catheter fluid to the sensor diaphragm (why use water, but not air?)
Blood Pressure Transducers

A thin flexible metal diaphragm is stretched across the opening of the transducer top.

The diaphragm is connected to an inductive bridge (or resistive Wheatstone bridge) strain gauge which flexes the strain gauge an amount proportional to the applied pressure.

A clear plastic dome, filled with fluid sits atop the diaphragm and provides the hydraulic coupling / connection to the catheter. Electrical connector typically houses the bridge circuit.
**Strain gage w/ Wheatstone Bridge**

Let all $R$ initially be equal to $R_0 \ll R_i$. If $R_1$ and $R_3$ increase and $R_2$ and $R_4$ decrease by $\Delta R$, then

$$\Delta V_0 = 0 \Leftrightarrow \frac{R_1}{R_2} = \frac{R_4}{R_3}$$

$$\Delta v_0 = \frac{\Delta R}{R_0} v_i$$
Arterial/Venous BP Transducers
Disadvantage of the previous system: The frequency response of the system is limited by the hydraulic properties, in particular the low pass filter effect of the tubing system.

Using an intravascular system eliminates the entire plumbing system, by making the measurement at the site!
- Eliminates the time delay introduced by the tubing system
- Allows high fidelity measurement of the high frequency components of the BP signal

Typical sensors used:
- Strain gages bonded onto a flexible diaphragm at the catheter tip
- Fiber optic systems where the displacement measurement of the diaphragm is made optically
Dynamic Properties of the Measurement System

- Errors in measurement of dynamic pressure can lead to significant consequences, underdamped system → Overestimated BP.
- The liquid filled catheter-sensor is a hydraulic system that can be best modeled by distributed parameters.

Each segment of the catheter has its own resistance $R_c$, inertance $L_c$, and compliance $C_c$. In addition, the sensor has resistor $R_s$, inertance $L_s$, and compliance $C_s$. The compliance of the diaphragm is $C_d$. 

$$C_d = \frac{\Delta V}{\Delta P}$$
(a) Simplified analogous circuit. Compliance of the sensor diaphragm is larger than compliance of catheter or sensor cavity for a bubble-free, noncompliant catheter. The resistance and inertance of the catheter are larger than those of the sensor, because the catheter has longer length and smaller diameter. (b) Analogous circuit for catheter-sensor system with a bubble in the catheter. Catheter properties proximal to the bubble are inertance $L_c$ and resistance $R_c$. Catheter properties distal to the bubble are $L_{cd}$ and $R_{cd}$. Compliance of the diaphragm is $C_d$; Compliance of the bubble is $C_b$. (c) Simplified analogous circuit for catheter-sensor system with a bubble in the catheter, assuming that $L_{cd}$ and $R_{cd}$ are negligible with respect to $R_c$ and $L_c$. 
10 harmonics would clearly be adequate to accurately represent the BP signal. Considering that the fundamental frequency should be around $1 \sim 2$ Hz, a $0 \sim 20$ Hz bandwidth should be sufficient for a bioamplifier used to condition BP signals.
Distortion will be seen on all signals acquired by a system that does not possess the appropriate frequency response.

(a) Recording of an undistorted left-ventricular pressure waveform via a pressure sensor with bandwidth dc to 100 Hz. (b) Underdamped response, peak value is increased. A time delay is also evident (c) Overdamped response showing a significant time delay and an attenuated response.
Heart sounds: Vibrations or sounds due to acceleration or deceleration of blood

Heart murmurs: Vibrations or sounds due to blood turbulence

Listening to the sounds made by the heart for diagnostic purposes is known as **auscultation**. The temporal relationship of these sounds and the mechanical/electrical events of the cardiac cycle provide significant diagnostic information ➔ **phonocardiography**
Heart Sounds
Heart Sounds

- **S1**: Movement of blood during the ventricular systole, asynchronous closure of the tricuspid/mitral valves
- **S2**: Closure of semilunar valves causing the deceleration and reversal of flow in the aorta and pulmonary artery
- **S3**: Termination of rapid filling of the ventricles from the atria
- **S4** (non-audible, but noticeable on phonocardiogram) contraction of atria and propelling of blood into the ventricles
- **Murmurs**: typically due to stenosis (constriction / blockage) or insufficiencies (leakages) of the heart valves
- Typical frequencies of HS and murmurs: 0.1 ~ 2000 Hz.
Indirect Measurements
Auscultatory Method

- Most commonly used technique for listening sounds and/or indirectly (non-invasively) measuring blood pressure is the auscultatory method.
- For NIBP, one listens to the Korotkoff sounds.
- Typically less then 200 Hz, where human hearing is not very acute, time consuming, but remarkably accurate.
**Indirect Measurements**

**Oscillometric Method**

- More commonly used in automated systems, less accurate
- The **vibrations** of the artery wall due to blood spurting are measured.

- Easy to obtain systolic and MABP, however, there is no clear indication of the diastolic pressure. Proprietary algorithms are used, instead.
Oscillometric Automated BP Monitors

Block diagram of the major components and subsystems of an oscillometric blood-pressure monitoring device, based on the Dinamap unit, I/O = input/output; MAP = mean arterial pressure; HR = heart rate; SYS = systolic pressure; DYS = diastolic pressure. From Ramsey M III.
**Indirect Measurements**

**Ultrasonic (Doppler) Method**

- Can be used for measuring BP as well as blood flow velocity (Doppler effect)
- \( P_{\text{dia}} < P_{\text{cuff}} < P_{\text{sys}} \) ➔ the artery opens and closes with every heart beat. The UT signals scattered from the artery backwall clearly indicate the opening /closing of the artery
- \( P_{\text{cuff}} = P_{\text{sys}} \) ➔ opening /closing coincide
- \( P_{\text{cuff}} = P_{\text{dias}} \) ➔ no closing signal is detected