CARDIOVASCULAR MONITORING

EE 471 – F2016

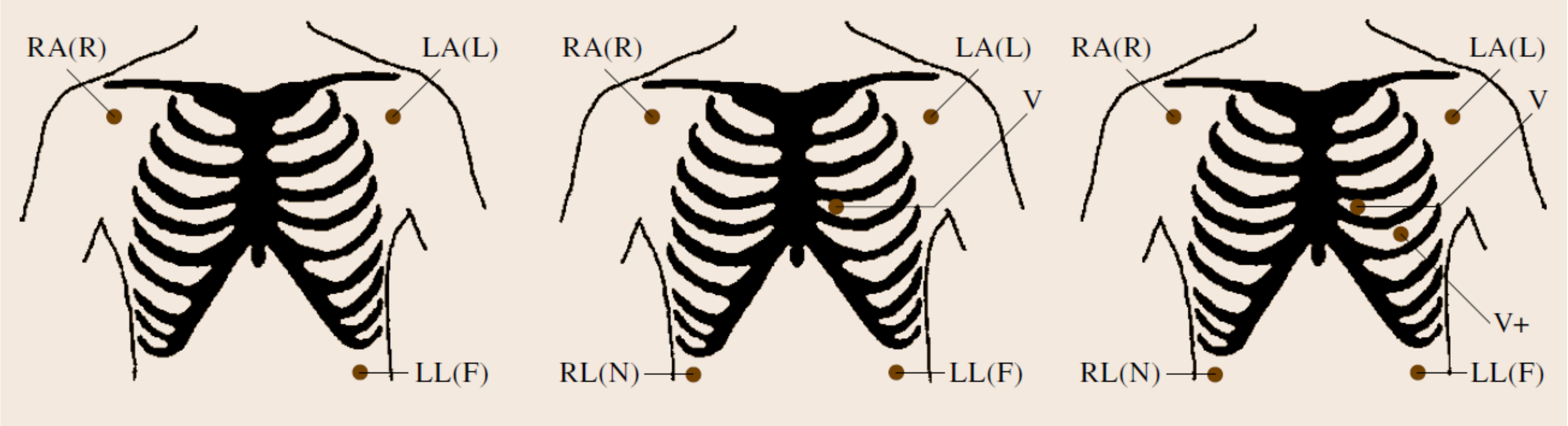
Prof. Yasser Mostafa Kadah

Introduction

- Cardiovascular monitoring covers monitoring of heart and circulatory functions
- It makes it possible to commence interventions quickly in the event of any impairment
- Measurements are used to assess the condition of the patient, reach a diagnosis, decide on therapy, and monitor therapy
- Covers cardiac function in the form of electrical phenomenon (ECG) and its mechanical effects including pressure build-up and volume delivery, contractility, preload, and afterload

Electrocardiogram (ECG)

- ECG provides information about heart rate and rhythm, excitation, conduction, and repolarization and disturbances in these functions
- ECG does NOT provide any direct information about the pumping capacity of the heart (i.e. mechanical cardiac

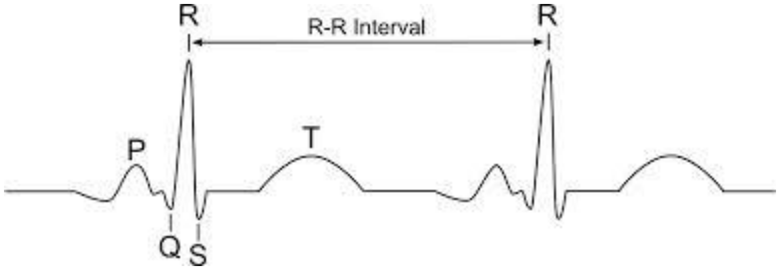


Lead Wire Color Code:

- IEC2 (US): RA: white, LA: black, LL: red, RL: green, V: brown, V+: gray/brown
- IEC1 (Europe): R: red, L: yellow, F: green, N: black, V: white, V+: gray/white

Heart Rate (HR)

- Heart rate (typical measuring range of 15–300beats/min) is determined as a moving average over a specific time (e.g. 10s), or a specified number of QRS complexes
- An alternative to the ECG that can be used when there are interferences in the ECG, e.g. during cauterization in the OT)
- Can be computed in the form of pulse rate from the arterial blood pressure or pulse curve from the SpO2 signal
- Basis of heart rate measurement is safe detection of QRS complexes in ECG and assessment of RR intervals



Hemodynamics

- Hemodynamics is the study of the flow of blood in the circulatory system
  - This flow is driven by the pressure generated by the heart.
- Since the pressure in the vascular system is highly dependent on activity and the position of the body (hydrostatic pressure), blood pressure measurements are always taken at rest and are based on the height of the heart (right atrium)
- Vascular system is functionally divided into low-pressure system (small, pulmonary circuit) and high-pressure system (large, systemic circuit), connected by the heart as driving element

Hemodynamics

- Heart generates pressure in its contraction phase (systole), by means of which stroke volume (SV) is expelled from the ventricle into arterial vascular system
  - Every stroke volume conveyed generates a pulse wave
- Peak pressure during the expulsion of stroke volume from ventricle is systolic blood pressure (highest point of pressure curve)
- Pressure at end of relaxation phase (diastole) is referred to as diastolic blood pressure (lowest point of pressure curve)
- Difference between systolic and diastolic pressure is blood pressure amplitude

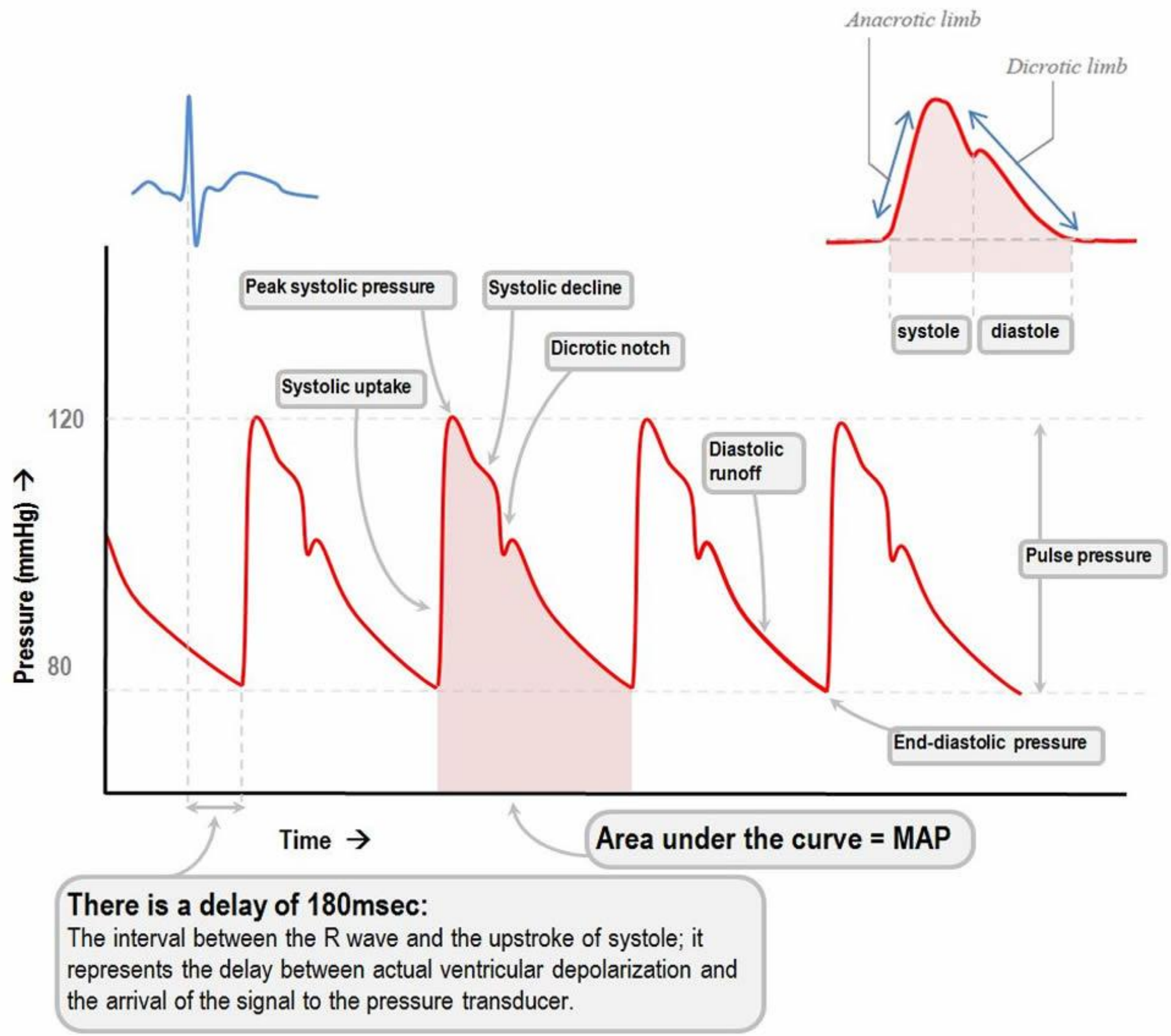
Hemodynamics

- Pressure that maintains blood flow in vascular system and act as driving force of perfusion is mean pressure
  - In systemic circuit mean arterial pressure is termed APm (also MAP)
  - In pulmonary circuit mean pulmonary artery pressure is termed PAPm
- Stroke volume depends on preload, contractility of myocardium and afterload
- Preload is stretching of myocardium brought about by passive filling of ventricles at end of diastole and is best described by end-diastolic volume
- Afterload is force exerted by cardiac muscles to overcome resistance in outflow tract of left ventricle and peripheral circuit
  - Mean arterial pressure and vascular resistance are measures of afterload

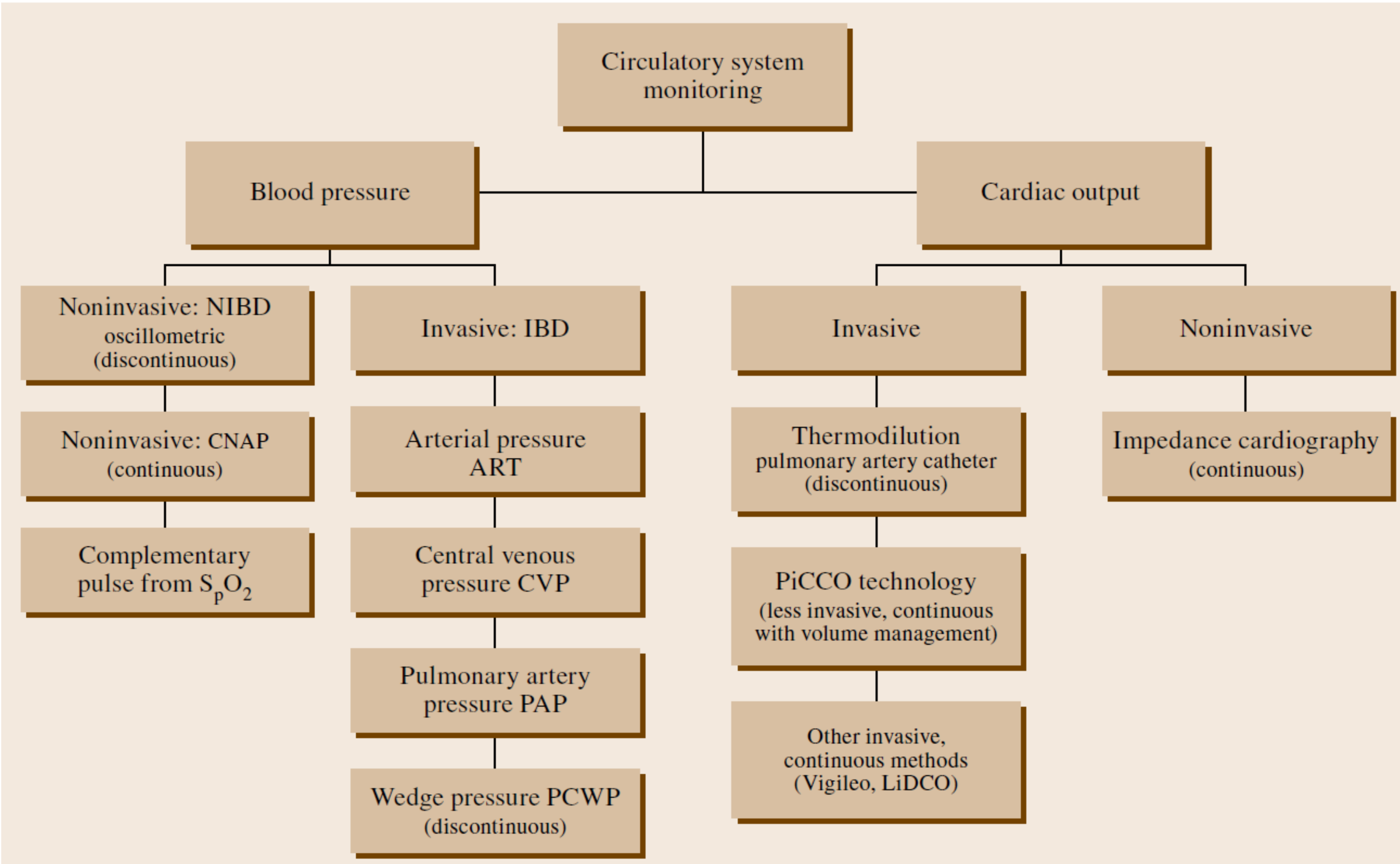
Hemodynamics

- Factors that also determine blood pressure behavior include elasticity of vascular system components, circulating blood volume and, in particular, peripheral vascular resistance, which is influenced by wall tension of vessels (vessel tone) controlled by sympathetic nervous system
- Delivery volume of blood per minute is known as the cardiac output (CO) and is the product of stroke volume and heart rate
- Control mechanisms in the body regulate circulation with aim of adjusting cardiac output to circulation required to supply oxygen to the organism and eliminate CO_2, keeping the blood pressure largely constant and adjusting the circulation in the individual organs and tissues to the functional state in each case

Hemodynamics

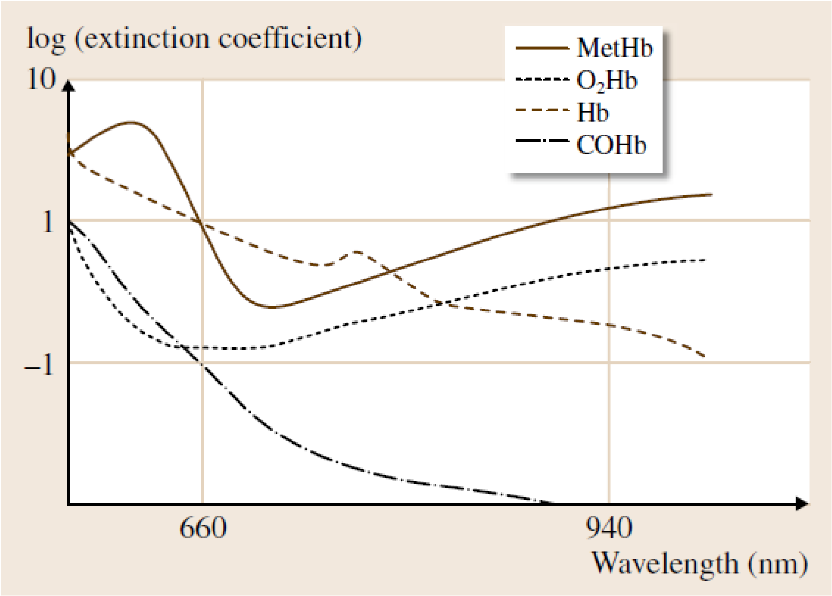


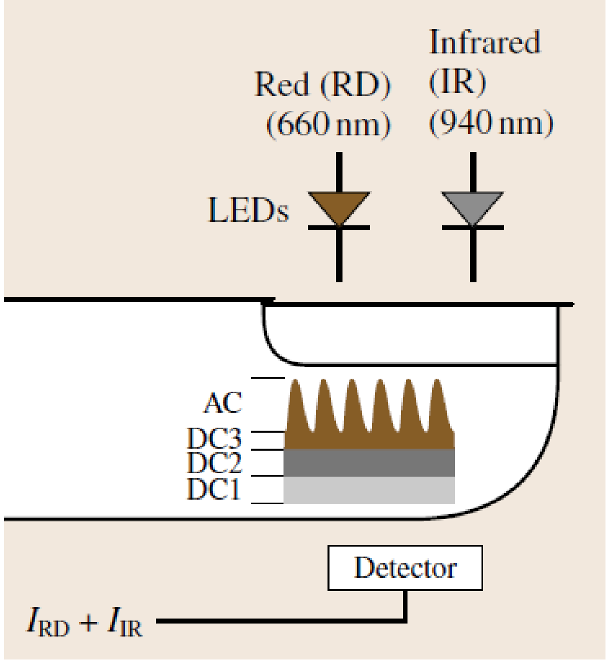
Hemodynamic Monitoring



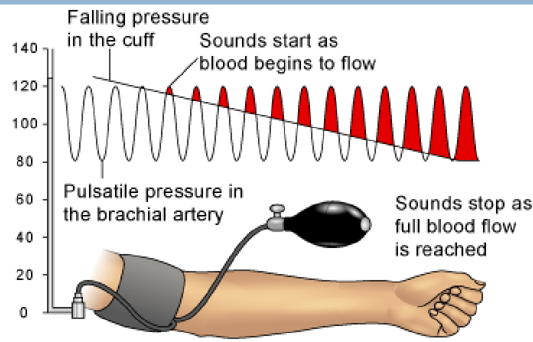
Pulse Monitoring

- Pulse monitoring is performed either invasively from the arterial pressure curve or noninvasively from the plethysmogram of pulse oximetry
  - Pulse monitoring has particular importance as a safety measure in such condition as monitoring pacemaker patients





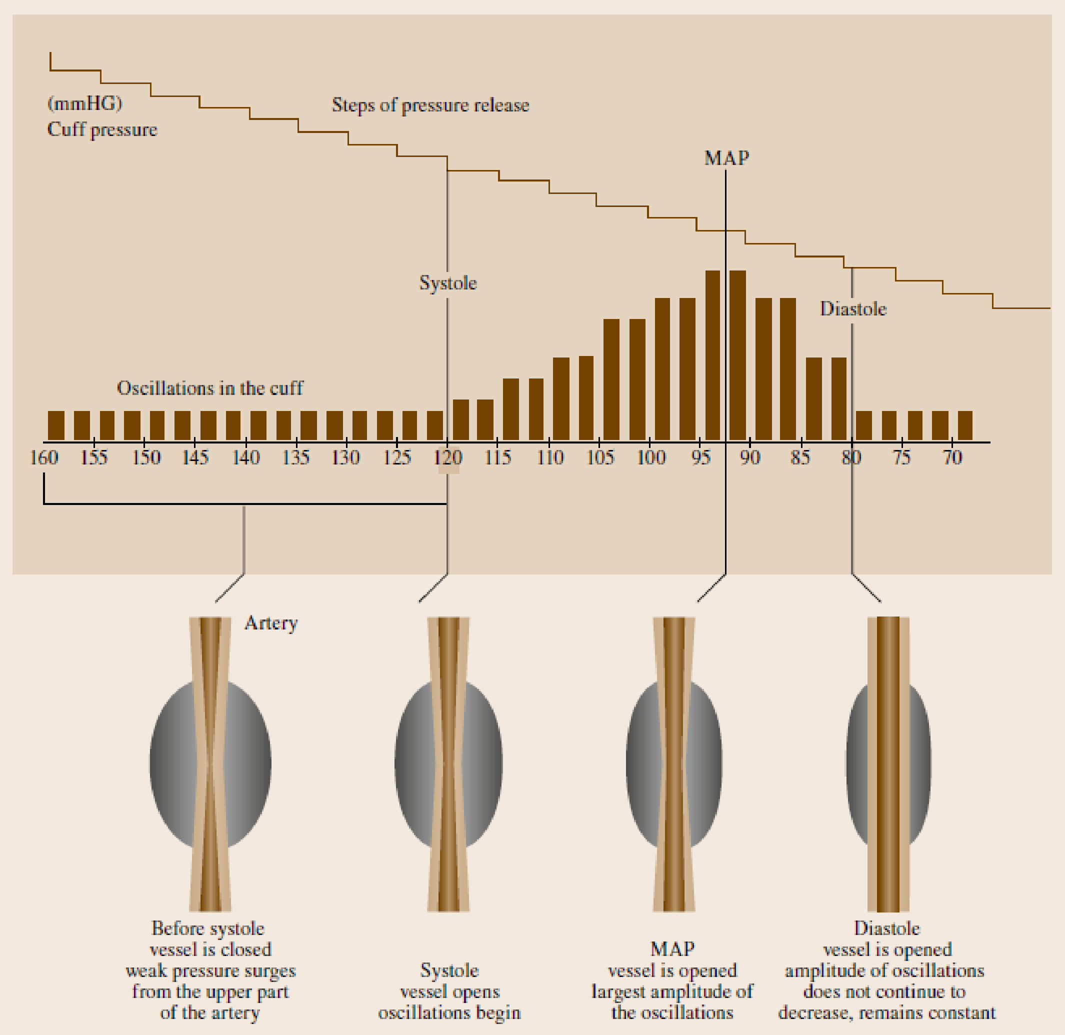
Discontinuous Noninvasive Blood Pressure (NIBP): Auscultatory Method



- Sphygmomanometer
  - Riva Rocci: Systolic blood pressure measurement
  - Korotkoff: Diastolic blood pressure
- Auscultatory Method
  - Cuff placed on exposed upper arm at the level of heart with middle of rubber bladder positioned over brachial artery
  - After palpating the brachial artery, the cuff is inflated to≈ 30mmHg above the pressure at which the pulse can no longer be detected
  - Stethoscope is placed against the brachial artery and the cuff pressure is slowly released.
  - Pulsation that then begins causes knocking noises (Korotkoff sounds phase 1): systolic blood pressure is read off from the manometer
  - Sounds change until sound can no longer be heard (phase 5) and is measured as the diastolic pressure

Discontinuous Noninvasive Blood Pressure (NIBP): Oscillometric Method

- When cuff pressure is released once the systolic pressure has been reached, the vessel walls begin to oscillate and maintain this behavior until the vessel is no longer occluded
- Oscillations are transmitted to air in cuff and are read on the manometer
- Today, oscillations are measured electronically using pressure sensors



Continuous Noninvasive Arterial Blood Pressure Measurement (CNAP)

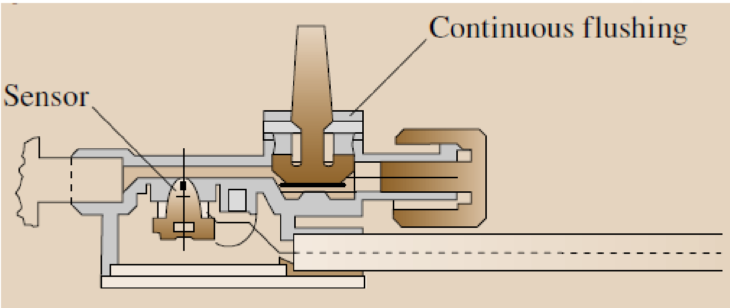
- Blood pressure is not always constant but can change within a matter of seconds
  - In particular, during anesthesia and its induction, variations in blood pressure can arise and require immediate medical attention
- Noninvasive technique of relaxed arterial wall (vascular unloading technique or volume clamp method) uses optical sensor in small cuff around finger to measure volume pulses due to each heart beat
  - Pressure in the cuff is regulated by means of feedback such that the optical measuring path always remains constant
- When a pulse occurs, cuff pressure is increased accordingly, and when the pulse subsides the cuff pressure is reduced.
  - Cuff pressure reflects the pressure occurring in the enclosed finger artery with high degree of accuracy

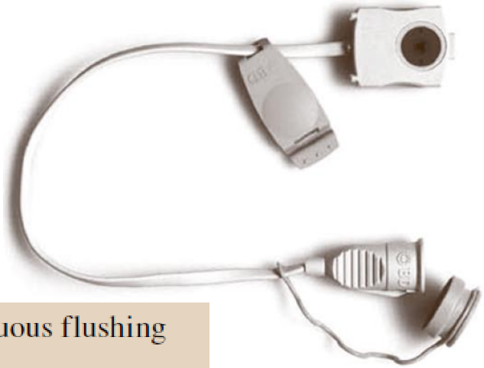
Continuous Noninvasive Arterial Blood Pressure Measurement (CNAP)

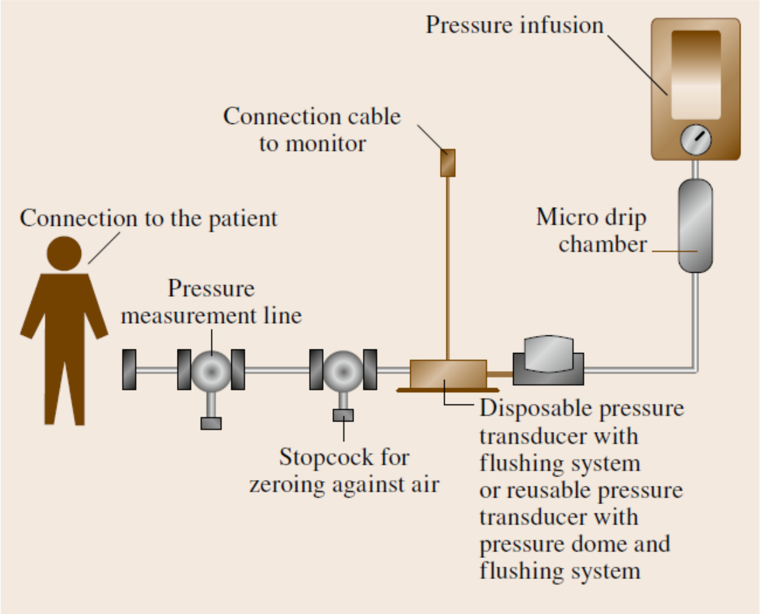
- CNAP uses pairs of sensor cuffs, which are placed on adjacent fingers
  - Only one cuff is used for measurement at any time, and after no longer than half an hour continuous measurement is automatically switched
- Venous stasis that naturally occurs during measurement on finger very quickly decreases once more after the switch
- Great advantage of this method is calibration of of continuous measurement with the normal NIBP measurement, so that correct values are displayed even when the fingers are not level with the heart
  - Advantages of both NIBP and CNAP

Invasive Pressure Measurement in High-Pressure System

- Continuous availability of measurement signal (pressure curve) and pressure values
  - Provides possibility of triggering an alarm if predefined limit values violated and of further signal processing of measurement data
- Connection is set up by means of an intra-arterial catheter between intravasal blood column and liquid-coupled pressure transducer







Invasive Pressure Measurement in Low-Pressure System

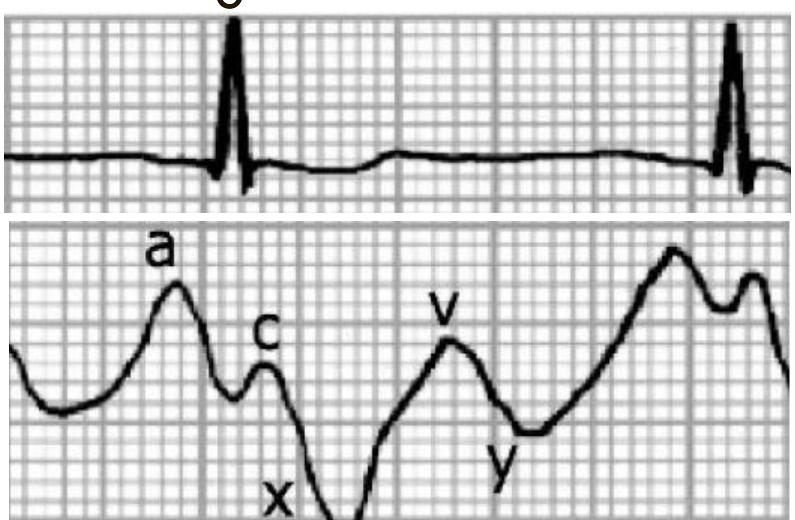
- Aim is to obtain information about right ventricular function, pulmonary circuit, and filling of vascular system
  - Central Venous Pressure (CVP)
  - Pulmonary Artery Pressure (PAP)
  - Pulmonary Capillary Wedge Pressure (PCWP)

Central Venous Pressure (CVP)

- Measurement of the central venous pressure is by means of a liquid manometer or a pressure sensor using central venous catheter (CVC) placed in superior vena cava at the entrance to the right atrium
- Pressure transducers have the advantage that measurement information is available continuously and certain signal characteristics of the CVP curve are additionally available
- Because of the small pressure values, it is important that pressure measurement system is situated level with the heart (correct zero point positioning) in order to avoid errors
  - Hydrostatic pressure difference can cause incorrect measurements

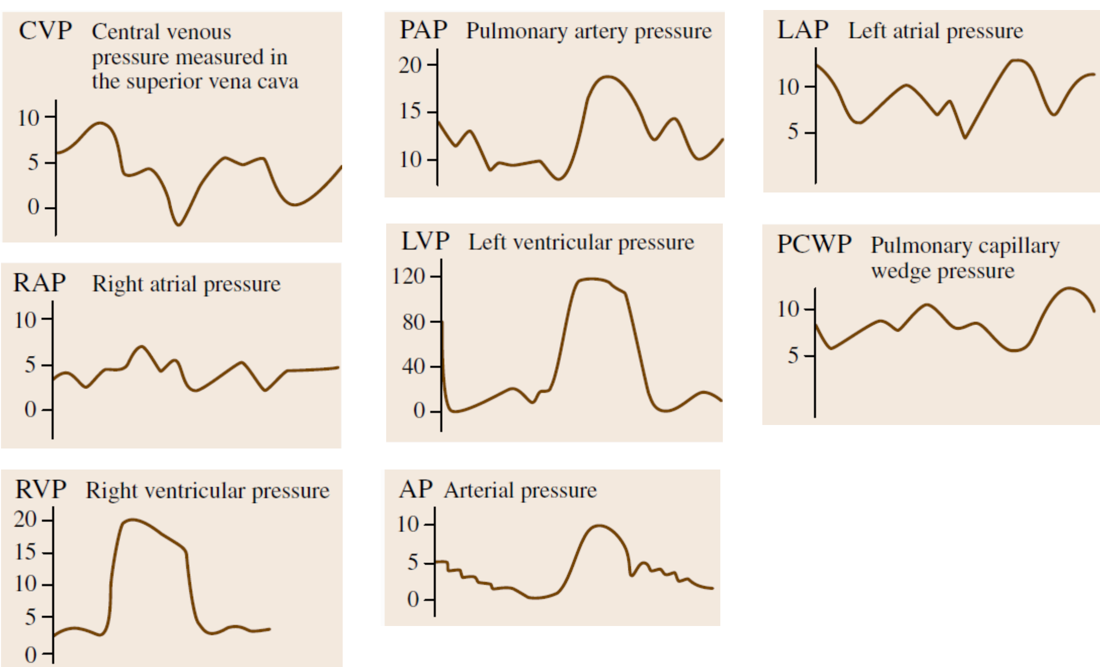
Central Venous Pressure (CVP)

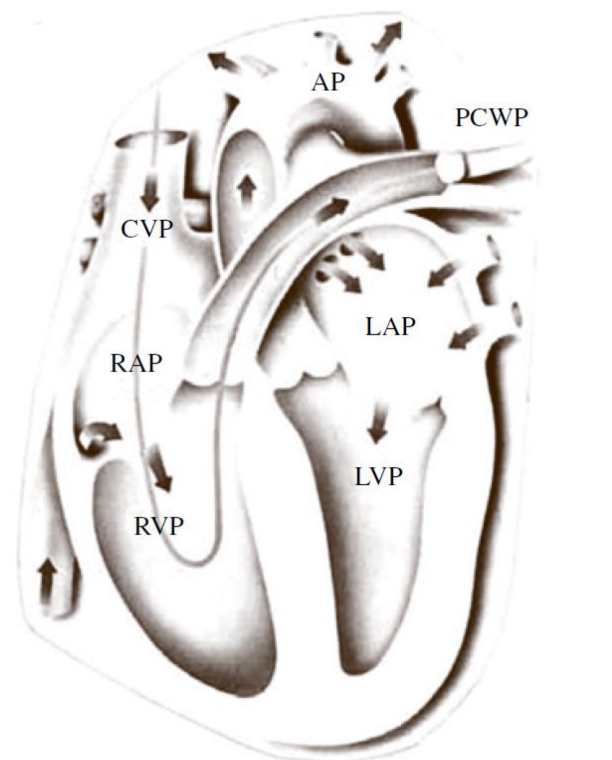
- Progression of CVP curve shows:
  - Atrial contraction (a-wave)
  - Beginning of the ventricular contraction (c-wave)
  - Relaxation phase (v-wave)
- Influenced by capacity of vascular system, cardiac output, blood volume, compliance of myocardium, and afterload of right ventricle



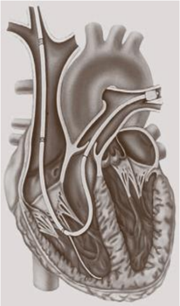
Pulmonary Artery Pressure (PAP) and Pulmonary Capillary Wedge Pressure (PCWP)

- To monitor hemodynamics of right ventricle, balloon catheter is pushed through venous system into right atrium, right ventricle, and then through pulmonary valve into arteria pulmonalis
  - Path of catheter is followed from different typical pressure curves





Pulmonary Artery Pressure (PAP) and Pulmonary Capillary Wedge Pressure (PCWP)



- Correct catheter position is reached once in wedge position
  - That is, once the inflated balloon of the catheter blocks off the pulmonary artery branch
- If tip of catheter rests against wall of pulmonary artery (pseudo-wedge), this causes damping of pressure curves when balloon is filled and there is continuous rise in pressure
- Although catheter is in right ventricle, in the wedge position pressure in left atrium can be inferred via the distal lumen
  - PCWP value corresponds in first approximation to the left atrial pressure (LAP) and thus to the end-diastolic filling pressure in the left ventricle
  - Left atrium, pulmonary capillaries, and pulmonary artery under normal conditions form a common pressure connection during diastole.

Balloon Catheters

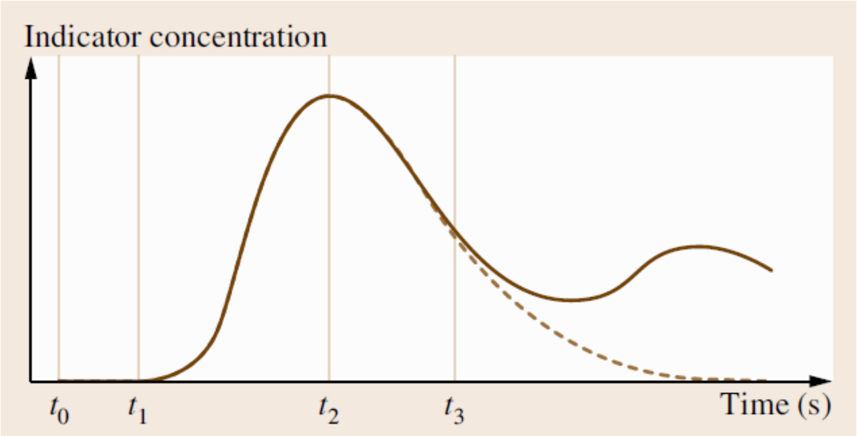
- Using balloon catheters (so-called flow-directed catheters, pulmonary artery catheters, or Swan–Ganz catheters) with different length and thickness, number of lumina, position of lumen exit sites, and other characteristics; CVP, PAP, and core body temperature can be measured simultaneously, and the PCWP and CO can be measured intermittently
- Specialized balloon catheters provide additional possibilities such as intracardial ECG measurement, supraventricular and ventricular stimulation, measurement of mixed venous oxygen saturation SvO_2 with integration of fiber optics, transluminal stimulation probe, or additional infusion lumina
- Balloon catheters are not free of risks and can cause complications such as:
  - Supraventricular and ventricular arrhythmias
  - Ventricular tachycardia or ventricular fibrillation (rarely)
  - Venous thrombosis (particularly with a low CO)
  - Sepsis (risk rises as the duration of catheterization increases)
  - Pulmonary infarction (due to catheter occlusion of peripheral pulmonary artery)
  - Pulmonary artery rupture (by balloon inflation or the catheter tip).

Determining the Cardiac Output (CO)

- Cardiac output is volume of blood conveyed per minute (l/min)
- Classical way of determining CO is by Fick's principle
  - Calculation is based quite simply on the law of conservation of mass
- CO is the quotient from oxygen consumption (VO_2) in the body and difference in oxygen content ($avDO_2$) between arterial blood flowing to the body and mixed venous blood returning from the body: $CO = VO_2/avDO_2$
  - Unfortunately, under routine conditions oxygen consumption cannot be measured with sufficient accuracy in the clinical environment

Dilution Methods to Measure CO

- Development of fundamental work of Stewart and Hamilton to determine CO by means of dye dilution (1920s)
  - Implemented with dye, cold, ions, radioisotopes dilution methods
- Introduction of thermistor catheter by Swan and Ganz (1970s) made thermodilution by means of a pulmonary artery catheter established as leading method for clinical use



Thermodilution Method

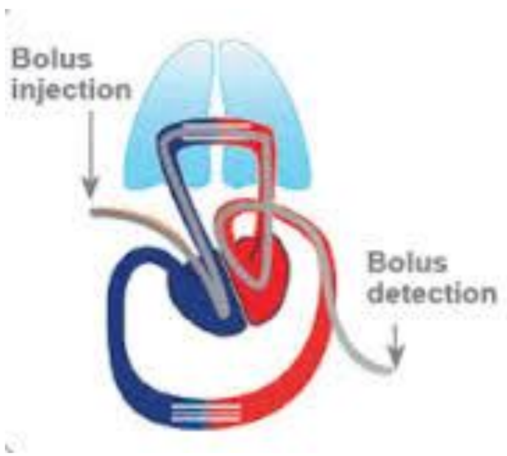
- Defined amount of saline solution at a temperature of 0–25 ◦C (the lower the temperature, the more accurate the measurement) is injected into the right atrium via proximal port of the multilumen pulmonary artery catheter
- Because injected fluid is mixed with warm flowing blood (37 ◦C) and is therefore diluted, change in temperature in blood stream can be measured by thermistor situated close to tip of catheter
- Shape and area of dilution curve change with cardiac output
- With known temperature of injected fluid and blood as well as known volume of injected fluid, measuring system determines CO from the area of thermodilution curve

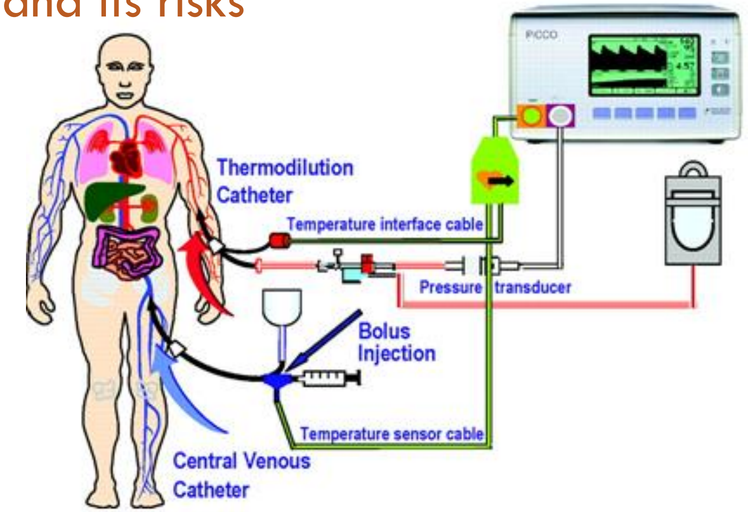
Thermodilution Disadvantages

- Need for the pulmonary artery catheter, the indication of which is viewed particularly critically
  - Connors *et al.* (JAMA, 1996): “RHC is associated with increased mortality and increased utilization of resources”!
- Discontinuity of measurements
  - This was overcome by emitting heat pulses to the blood using a special pulmonary artery catheter and by evaluating their dilution curve
  - Since heat pulses can be applied at very short intervals (30–60 s), this virtually provides continuous measurement

PiCCO Technology

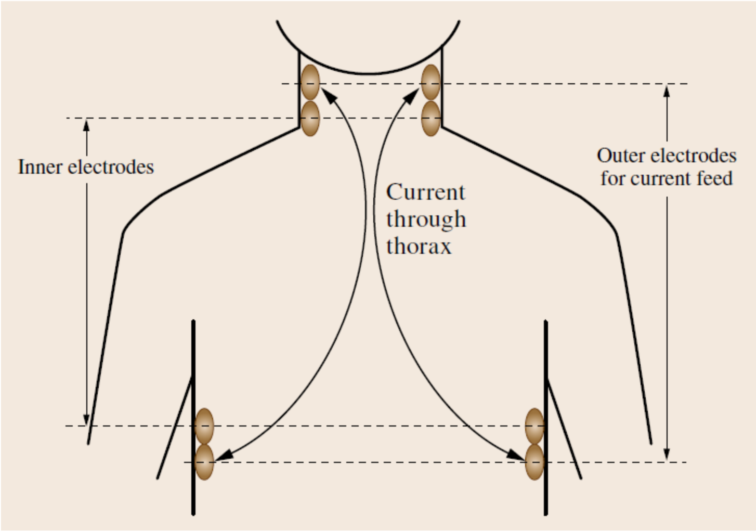
- Thermodilution can, in principle, be done transpulmonarily
  - Cold bolus passes through lungs with thermistor placed in arterial system
- Cold bolus is injected into right atrium as in normal thermodilution except with normal central venous catheter (more common)
- Temperature profile is measured in arteria femoralis
- Advantage of this method is that it is less invasive
  - Omission of pulmonary artery catheter and its risks





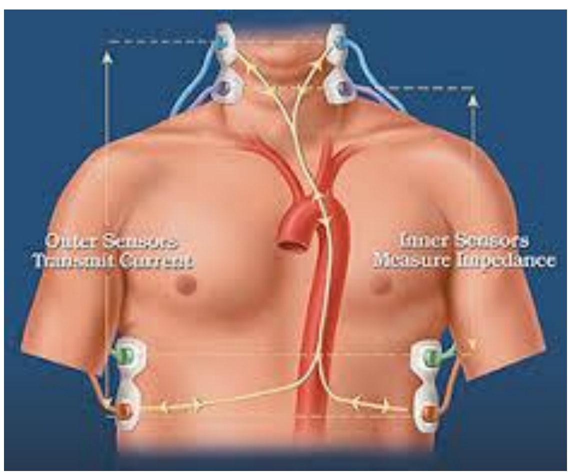
Impedance Cardiography

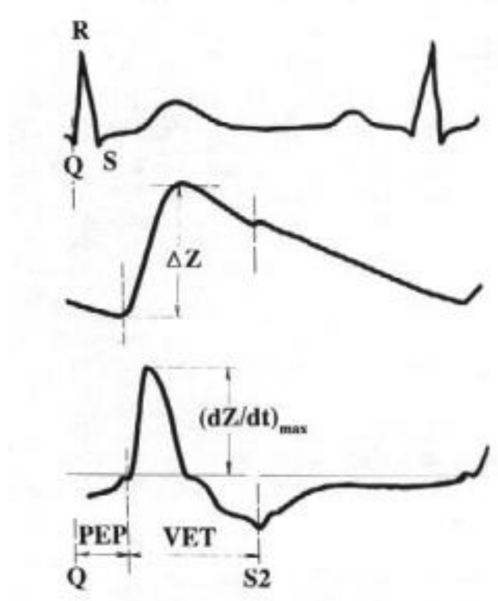
- It has long been known that blood volume expelled with each heart beat (stroke volume) leads to measurable variations in the thoracic impedance
  - Attempts to determine the stroke volume and CO from the variations in thoracic electrical bioimpedance (TEB)
- Offers several advantages
  - Completely noninvasive and low risk
  - Continuous beat-to-beat measurement
  - Easy to apply
- Cannot be used in some cases
  - Example: septic shock patients
  - PiCCO is used more due to that



Impedance Cardiography

- Weak high-frequency constant current (e.g. 2.5mA, 70 kHz) is passed through thorax by means of external ring electrodes (or special double electrodes) arranged on neck and thorax
- Current seeks path of least resistance, which is essentially blood-conducting aorta and voltage drop is measured by inner measuring electrodes





ICG

Calculation of Hemodynamic Variables

- Total Peripheral Resistance (TPR), also called Systemic Vascular Resistance (SVR), is resistance of systemic circuit, computed as quotient of propulsive pressure difference (Mean Arterial Pressure APm - Central Venous Pressure CVP) and flow (CO)

$$\boxed{SVR = (APm - CVP)/CO} \quad \text{dyn s/cm}^5$$

- Pressure difference in small circuit is Mean Pulmonary Pressure minus Wedge Pressure PCWP (as a measure of the left atrial pressure). The Pulmonary Vascular Resistance (PVR) is given as:

$$\boxed{PVR = (PAPm - PCWP)/CO} \quad \text{dyn s/cm}^5$$

Reading Assignment

- Read Chapter 48 of *Springer Handbook of Medical Technology*