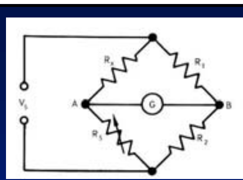

HEMODYNAMIC MONITORING: FROM PRINCIPLES TO PRACTICE

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SUMMARY

- Fluid-filled catheters are commonly utilized in the ICU to measure a variety of physiologic parameters
  - Systemic blood pressures
  - Pulmonary blood pressures
  - Intra-abdominal pressure
  - Intracranial pressure
- To appropriately assess and utilize the data provided by such monitoring devices, certain basic concepts must be understood

INTRODUCTION

- Invasive pressure monitoring in the critically ill provides valuable information
  - Most accurate method for determining blood pressure
  - Allows continuous physiologic monitoring
  - Identifies physiologic abnormalities
  - Can be used to guide appropriate resuscitative therapies
  - Waveform interpretation provides valuable information on the patient’s cardiac contractility and heart valve competency

INTRODUCTION

- To improve patient outcome, accurate measurement of physiologic variables requires:
  - Constant vigilance to ensure accuracy
  - Thorough understanding of monitoring principles and pitfalls
  - Appropriate application of information gained
- WARNING: Physics lies up ahead! If you developed PTSD following college physics, you may want to skip the remainder of this lecture (relax, it’s actually pretty cool and explains why you needed to take physics after all)

G-I-G-O

- “Garbage In…Garbage Out”
  - Erroneous physiologic measurements can result in inappropriate patient therapy
  - You should always ask “Is this data valid?”
  - Example
    - » Diebel et al. found that 52% of PAOP measurements in surgical patients are inaccurate and misleading as a result of monitoring artifacts
    - » Reliance upon erroneous PAOP and CVP values to resuscitate critically ill patients may lead to under-resuscitation and inappropriate therapy

MEASURING PRESSURE VARIABLES

- Each fluid-based pressure monitoring system has the following components
  - Intravascular catheter
  - Connecting tubing and stopcocks
  - Pressure transducer
  - Continuous flush device
  - Amplifier
  - Oscilloscope / Digital display
  - Processor
  - Recorder

Intravascular catheter; Connecting tubing and stopcocks; Pressure transducer; Continuous flush device	Hydraulic system
Amplifier; Oscilloscope / Digital display; Processor; Recorder	Electronic system

MEASURING PRESSURE VARIABLES

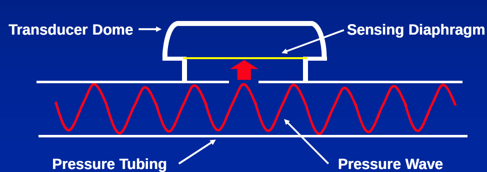
- The hydraulic system is much more subject to potential errors and artifacts than is the electronic system
  - Learning to troubleshoot the hydraulic portion of a invasive pressure monitoring system is essential
    - » Confirms the validity of the data
    - » Helps avoid inappropriate therapeutic interventions based upon erroneous data

HYDRAULIC SYSTEM COMPONENTS

- Intravascular catheter
  - Tubing to access the desired blood vessel or compartment
  - Detects the pressure waves generated by cardiac contraction
- Connecting tubing and stopcocks
  - Transmits pressure wave from patient to measuring device
  - Allows control of blood vessel to avoid hemorrhage, introduction of air, etc…

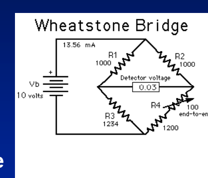
PRESSURE TRANSDUCER

- Converts the mechanical impulse of a pressure wave into an electrical signal through movement of a “strain gauge”
  - Modern transducers utilize a displaceable silicon sensing diaphragm and a “Wheatstone Bridge”



WHEATSTONE BRIDGE

- An electrical circuit for comparison of resistances
- Consists of a power source and four resistors, three of which have a known resistance
- To determine the unknown resistance, the resistance of the other three are balanced until the current passing through both sides of the parallel “bridge” decreases to zero



WHEATSTONE BRIDGE

- The Wheatstone Bridge is used to measure the resistance change in a strain gauge
  - The resistance change is proportional to the changing physiologic variable (i.e. pressure) or mechanical strain applied to the transducer
  - “Zeroing” a transducer is simply determining the value of the unknown resistance at rest
    - » “Balancing the bridge”
  - As the physiologic variable changes, the resistance varies proportionally, a current is induced across the bridge, and the voltmeter value is converted to a pressure measurement

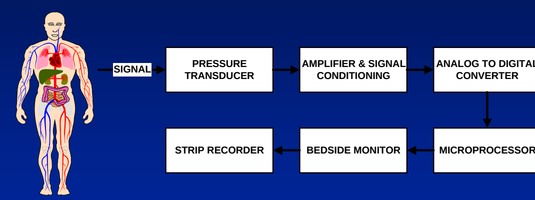
HYDRAULIC SYSTEM COMPONENTS

- Continuous flush device
  - Flushes the tubing with fluid at a rate of 1-3 mL/hr and helps prevent blood from clotting off the catheter
  - The “fast flush” feature increases the flow to 30 mL/min and can be used to test the system’s compliance

ELECTRONIC SYSTEM COMPONENTS

- Amplifier
  - Increases the low voltage signal from the pressure transducer to a signal that can be displayed
  - Most include electronic filters to remove unwanted physiologic “noise”
- Oscilloscope / Digital display
  - Used to display waveforms and numerical data
- Processor
  - Used to calculate various hemodynamic parameters
- Recorder
  - A printer, strip chart recorder, or other device

MEASURING PRESSURE VARIABLES



TYPICAL RADIAL ARTERY PRESSURE MONITORING SYSTEM

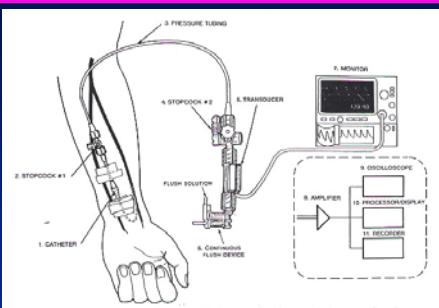


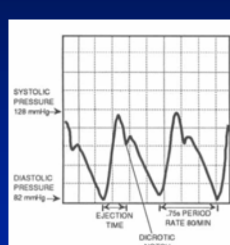
FIGURE 56-1. Components used to monitor blood pressure directly are nearly the same, independent of whether the catheter is in an artery (radial, brachial, or femoral) or in the pulmonary artery. The size of the transducer and plumbing components were enlarged for the illustration. (Adapted from Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. *Crit Care Med* 1986;14:651.)

CLINICAL CORRELATION

- What do these measurements mean clinically?
  - Systolic pressure
    - » The pressure exerted on the artery walls due to left ventricular contraction (i.e., contractility)
  - Diastolic pressure
    - » The pressure exerted during left ventricular relaxation (i.e., vascular resistance)
  - Pulse pressure
    - » The difference between peak systolic and diastolic pressures (i.e., perfusion)

CLINICAL CORRELATION

- What do these measurements mean clinically?
  - Dicrotic notch pressure
    - » The pressure that reflects aortic valve closure
  - Heart rate
    - » The frequency of contraction measured in beats per minute
  - Ejection time
    - » The time of left ventricular ejection

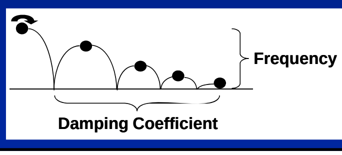


PHYSICS OF PRESSURE MONITORING

- The typical catheter-transducer system in the ICU is considered to be a “second-order dynamic system”
  - The pressure waveform dampens over time
  - Determined by two factors
    - » “Natural frequency”
      - The number of oscillations per unit time that occurs without any damping
    - » “Damping coefficient”
      - The time taken to dampen the waveform

PHYSICS OF PRESSURE MONITORING

- For example, when dropped onto a hard floor, a ball bounces several times before coming to rest
  - With each successive bounce, it does not rise as high as on the previous bounce
  - Each bounce has a characteristic *frequency* (the number of oscillations per unit time) and ***damping coefficient*** (time that it takes the ball to come to a rest)



PHYSICS OF PRESSURE MONITORING

- However, if the same ball is dropped onto soft earth, the ball will not bounce as high, resulting in a decreased frequency, and will come to rest sooner, reflecting an increased damping coefficient
  - This can be expressed mathematically BUT you don't need to know how to calculate it ☺

$$\frac{P_2}{P_1} = \frac{1}{\frac{f^2}{-F_n^2} + 2j\xi\frac{f}{F_n} + 1}$$

P_1, P_2 are output and input signals of the pressure transducer respectively, f is an arbitrary frequency, F_n is the natural frequency, ξ is the damping coefficient, and j is the complex number

PHYSICS OF PRESSURE MONITORING

- The accuracy of a second-order system is subject to three mechanical factors
  1. Compliance
     - The stiffness of the fluid-filled system (tubing)
  2. Fluid inertia
     - The pressure required to move fluid (blood) through the system
  3. Fluid resistance
     - The viscosity of the fluid moving through the system (resistance due to friction)

DETERMINING THE NATURAL FREQUENCY AND DAMPING COEFFICIENT

- This can also be expressed mathematically BUT you don't need to know how to calculate it ☺

$$F_n = \frac{1}{2\pi\sqrt{IC}} \qquad \xi = \frac{R}{2}\sqrt{\frac{C}{I}}$$

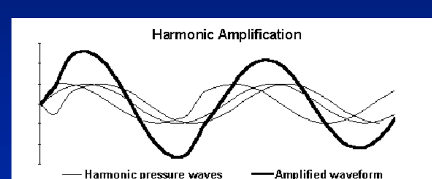
F_n is the natural frequency, ξ is the damping coefficient, C = compliance, I = inertia, and R = resistance

PHYSICS OF PRESSURE MONITORING

- The complex pressure wave generated with each beat of the heart is not unlike the bouncing ball
  - A pressure waveform is propagated at a given frequency (beats per minute)
  - The vascular resistance acts as the damping coefficient and diminishes the waveform's energy and magnitude over time
- The resulting arterial sine wave, occurring at the rate of the patient's pulse, is called the ***first harmonic*** or ***fundamental***

PHYSICS OF PRESSURE MONITORING

- If the waveform is reflected off a transducer or other obstruction within the catheter-tubing system, a wave reflection or "harmonic" is generated
  - These harmonic waveforms are additive and can introduce error into pressure measurements

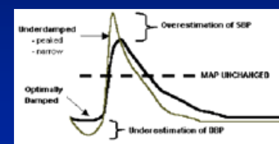


PHYSICS OF PRESSURE MONITORING

- Without some degree of damping within a system, pressure waves reverberate within the catheter and tubing leading to the formation of harmonics and overestimation of true blood pressure
  - An "*underdamped*" system
- With too much damping, the frictional forces impede the arterial waveform such that it loses energy leading to underestimation of blood pressure
  - An "*overdamped*" system

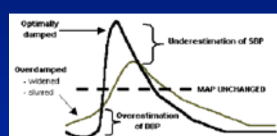
UNDERDAMPED WAVEFORM

- Note the characteristic narrow, peaked waveform
  - Overestimates systolic and underestimates diastolic blood pressure
  - Mean arterial pressure remains unchanged!
- Causes
  - Long stiff tubing, increased vascular resistance



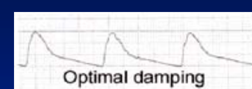
OVERDAMPED WAVEFORM

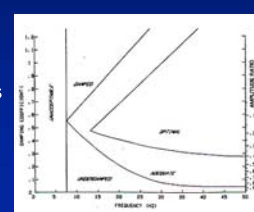
- Note the characteristic widened and slurred waveform
  - Underestimates systolic and overestimates diastolic blood pressure
  - Mean arterial pressure remains unchanged!
- Causes
  - Air bubbles, compliant tubing, catheter kinks, blood clots / fibrin, stopcocks, no fluid or low flush bag pressure



OPTIMAL DAMPING

- Some damping is essential to avoid harmonics
  - The "optimal" amount of damping is crucial to accurate measurement of physiologic pressures
- A catheter-transducer system accurately measures pressure only if its natural frequency and damping coefficient are appropriate





FREQUENCY RESPONSE

- A pressure monitoring system should be able to detect changes quickly (known as the "frequency response")
- Damping will tend to decrease frequency response
  - Important if changes are occurring rapidly such as with tachycardia or a hyperdynamic heart
- The ideal monitoring system has a high "natural" or "undamped" frequency
  - The frequency that would occur in the absence of any frictional forces or damping
  - Allows accurate measurement of fast heart rates

DYNAMIC RESPONSE ARTIFACTS

- Underdamped and overdamped waveforms are encountered in the ICU on a daily basis
  - Look for them at the bedside!
- The ability to recognize when these potential sources of error or "dynamic response artifacts" are present is essential to the…
  - Appropriate use of hemodynamic measurements
  - Prevention of inappropriate therapy based upon erroneous data

DYNAMIC RESPONSE ARTIFACTS

- Because dynamic response artifacts are commonly encountered during patient monitoring, titration of medications should ALWAYS be based upon mean arterial pressure (MAP)
  - This variable is less subject to measurement error due to under- or overdamping
- Systolic and diastolic blood pressure should NOT be used to titrate therapy!

TROUBLESHOOTING

- OK, now let's get practical…
- The simpler the pressure monitoring system, the higher its fidelity, the less it is subject to dynamic response artifacts, and the less likely it will be to produce erroneous data
- There are a number of steps that should be undertaken whenever setting up or troubleshooting a catheter-transducer system

TROUBLESHOOTING

- Remove multiple stopcocks, multiple injection ports, and long lengths of tubing whenever possible
  - The optimal length of pressure tubing is 4 feet
    - » Longer lengths of tubing promote harmonic amplification and underdamping
  - Ensure that arterial pressure tubing is being used
    - » Overly compliant tubing leads to overdamping
  - Avoid large diameter tubing
    - » Prevents achievement of optimal damping

TROUBLESHOOTING

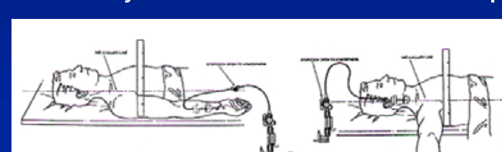
- Remove all air bubbles from the system
  - Perhaps the single most important step in optimizing dynamic response
    - » Air acts as a "shock absorber"
      - Bubbles as small as 1 mm in diameter can cause substantial waveform distortion
    - » Leads to overdamping and flattened waveforms
  - Ensure that all connections are tight and periodically flush all tubing and stopcocks to remove air bubbles

TROUBLESHOOTING

- Whenever you are evaluating a patient's changing hemodynamics
  - Check all transducers, stopcocks, tubing, and injection ports for air
  - Gently tap the tubing and stopcocks as the continuous flush valve is opened to dislodge any bubbles
    - » This will usually clear the system and restore measurement accuracy
    - » Flushing a few <u>small</u> bubbles through the catheter is OK; if more air is present, aspirate it from the tubing

TROUBLESHOOTING

- Zero the transducer
  - The accuracy of invasive pressure measurements is dependent upon a proper reference point
    - » The "midaxillary line" or "phlebostatic axis" is commonly utilized
  - Each transducer should be zeroed at least once each day and whenever data is considered suspect



TROUBLESHOOTING

- Transducers may be attached to the patient or to a pole at the head of the bed
- Changes in bed positioning generally require re-zeroing the pressure transducer
  - If the transducer is below the phlebostatic axis, the resulting arterial pressure will be erroneously high
  - If the transducer is above the phlebostatic axis, the resulting arterial pressure will be erroneously low

TROUBLESHOOTING

- The "fast-flush" or "square wave" test
  - Performed by opening the continuous flush valve for several seconds creating a square wave
    - A system with appropriate dynamic response characteristics will return to the baseline waveform within one to two oscillations
    - If dynamic response characteristics are inadequate, troubleshoot the system until acceptable dynamic response is achieved

CONCLUSIONS

- Direct pressure monitoring is essential for determining immediate changes in blood pressure
- The arterial waveforms provide valuable diagnostic and treatment information
- If not accurate, the erroneous data within these waveforms can potentially lead to detrimental treatment
- Look at both the bedside monitor *waveforms* AND the numerical data
  - The waveforms can tell you a great deal

CONCLUSIONS

- All hemodynamic data should be considered erroneous until you are satisfied that the dynamic response characteristics of the monitoring system are appropriate
- Learn to troubleshoot each monitoring system so that you can ensure the accuracy of your patient's data
- Physics is important after all ☺