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

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

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

Hydraulic system

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 an 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**

- PRESSURE TRANSDUCER
- AMPLIFIER & SIGNAL CONDITIONING
- ANALOG TO DIGITAL CONVERTER
- DIGITAL DISPLAY
- BEDSIDE MONITOR
- MICROPROCESSOR
- STRIP RECORDER

**TYPICAL RADIAL ARTERY PRESSURE MONITORING SYSTEM**

**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)

**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 ⚡
  \[
  \frac{P_2}{P_1} = \frac{1}{F^2 + 2j\xi F + 1}
  \]
  \(P_1, P_2\) are output and input signals of the pressure transducer respectively, \(f\) is an arbitrary frequency, \(f_p\) is the natural frequency, \(\xi\) 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)

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

- This can also be expressed mathematically BUT you don’t need to know how to calculate it ⚡
  \[
  f_p = \frac{1}{2\pi\sqrt{IC}} \quad \xi = \frac{R}{2\sqrt{I}}
  \]
  \(f_p\) is the natural frequency, \(\xi\) is the damping coefficient, \(C = \) compliance, \(I = \) inertia, and \(R = \) resistance

DETERMINING THE NATURAL FREQUENCY AND DAMPING COEFFICIENT

- 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

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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

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

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

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 small bubbles through the catheter is OK; if more air is present, aspirate it from the tubing

- 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 ☺