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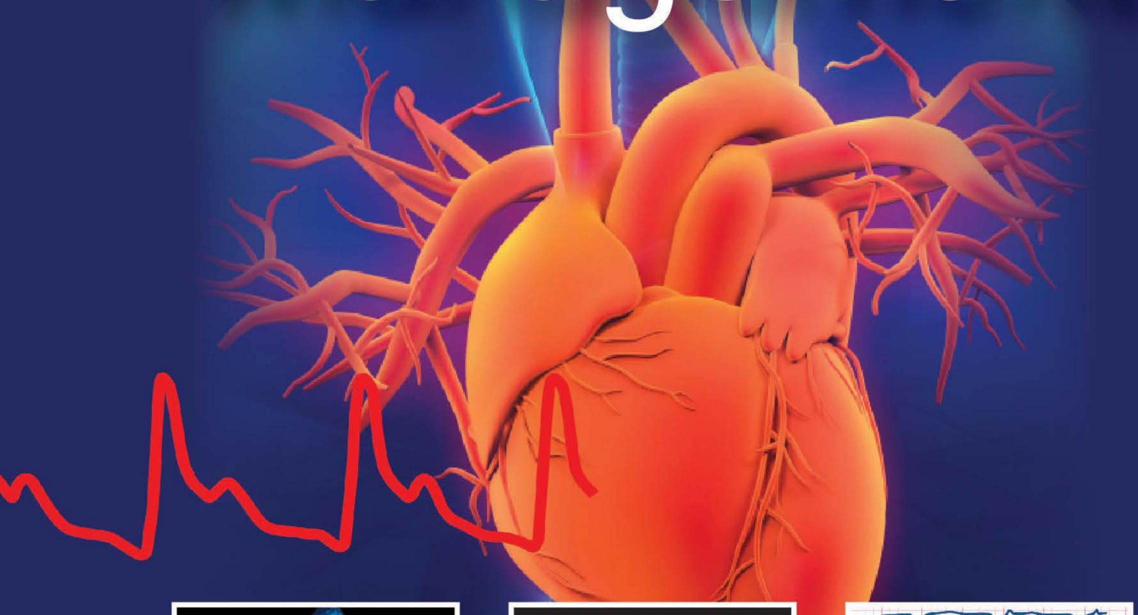
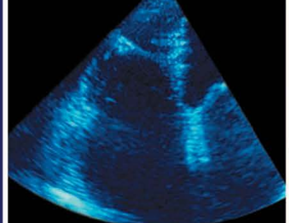
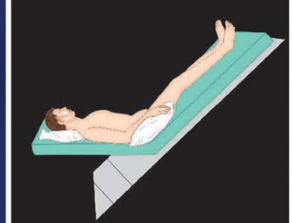
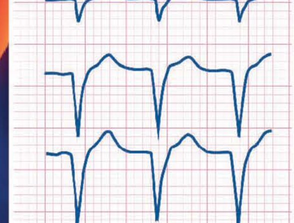
Workbook on Hemodynamic Management









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Foreword
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Basic Hemodynamic Monitoring

CHAPTER 15

Understanding the Transducer Assembly for Invasive Pressure Monitoring

Atul P Kulkarni, Suhail S Siddiqui, Syed Nabeel Muzaffar

INTRODUCTION

Circulatory shock is common in intensive care unit patients. A large multicenter study showed that the etiology of various types of circulatory failure was septic shock (62%), cardiogenic (16%), hypovolemic (16%), obstructive (2%), and other types of distributive shock (4%).[1] Current resuscitative strategies target variables such as mean arterial blood pressure, cardiac output, central venous pressure, and urine output. In low flow states like circulatory shock, the noninvasive blood pressure monitoring is unreliable.

An important component of invasive pressure measurements is the pressure transducer. Intensivists should be familiar with the basic principle of transducers, indications for their use, and the associated complications.

TRANSDUCER

Transducer is a device that converts energy from one form into another form. Pressure transducers convert kinetic energy (mechanical impulse of pressure waveforms, arterial, venous and intracranial) into an electrical energy (signal), which is further processed and displayed on a screen in a digitized form.[2] Two types of transducers are currently available:

1. Intravascular pressure transducer with sensor on catheter tip placed directly within blood vessel (this system is prone to thrombus deposition and error).
2. External transducer which is connected to pressure source by a fluid-filled tubing and catheter (hydraulic coupling) and this type of transducer is the most commonly used transducer in clinical practice.

Principle of Transducer

Transducer works on the basis of a strain gauge, in which short pieces of wire are connected to a diaphragm. Transmission of pressure waveform distorts the shape of diaphragm and alters the length of attached wires. Increase in length of wires alters their resistance, which is further converted into an electric signal by a Wheatstone bridge circuit.[3]

Wheatstone bridge circuit is an electrical circuit that measures electrical resistance by balancing two legs of a bridge circuit (two pairs arranged in a quadrangular format); one leg of a pair is formed by the unknown resistance.

Pressure Monitoring System Components and Transducer Setup

Pressure monitoring system includes a number of components like arterial or venous catheter, fluid-filled extension tubing (not more than 1.2 meters in length), stopcocks, continuous flush device, pressure bag (maintaining around 300 mm Hg pressure in the system), and an electronic cable connecting the transducer to bedside monitor.

The monitoring system should be thoroughly de-aired to prevent errors in measurement and the dreaded complication of cerebral air embolism. Stopcocks provide sites for blood sampling and allow establishment of a zero reference value. Newer systems have needleless blood sampling ports and in-line blood aspiration systems to reduce blood loss and line related infection risk. The flush device provides a continuous infusion of saline at the rate of 1–3 mL/hr to prevent retrograde blood flow or thrombus formation. It has a spring-loaded valve for periodic high pressure flushing of monitoring line manually and also to check for the optimal functioning of the system doing dynamic response test (also known as fast flush test or square wave test).

Transducer Setup

Zeroing: Once connected to monitor, the transducer is zeroed by exposing it to ambient atmospheric pressure through an open stopcock and pressing zero on the bedside monitor display screen. After zeroing, the transducer will measure all pressures with reference to atmospheric pressure.

If unexpected changes in pressure occur over time, zeroing should be checked again by opening the stopcock to atmospheric pressure. If pressure trace does not correspond to the zero pressure line, baseline drift in electrical circuit of transducer may have occurred and zeroing should be done again.

Leveling: Leveling is the final step in transducer setup in which zero reference point is assigned to a specific reference position on patient's body (structure of greatest interest), which is taken to be the position of heart (right atrium) for hemodynamic measurements, and the position of circle of Willis for intracranial pressure monitoring.

It has been found that the reference level for position of heart is an axis which runs transversely through thorax at the junction of a plane passing cross-sectionally through fourth intercostal space with a plane passing through mid-axillary line (midway between posterior surface of body and base of xiphoid process of sternum). This is also known as the phlebostatic axis.

Fourier Analysis

The arterial pressure waveform is a complex waveform. It consists of a fundamental wave (the pulse rate; also known as base sine wave or first harmonic) and a series of other harmonic waves, which are sine waves of smaller amplitudes and higher frequencies. This process of analyzing a complex waveform in terms of its fundamental frequency and the constituent harmonics is called Fourier analysis.[4]

In order to produce an accurate representation of the original waveform, the waveform is broken down into its component sine waves by a microprocessor, and the final waveform is regenerated from the fundamental frequency and its first eight harmonics. At least ten harmonics are required to represent the pulse pressure and eight harmonics must be analyzed to represent the arterial pressure waveform with sufficient resolution to see the dicrotic notch. For arterial blood pressure, the frequency equates to the heart rate per second. Therefore, for heart rates of up to 180/min (fundamental frequency = 3 Hz), the system should be able to reproduce waveforms of up to 24 Hz.

Natural Frequency and Resonance

Every object or material has a frequency at which it freely oscillates and this is called as its natural frequency. If a second energy source (arterial pressure wave) is introduced into a system with its inherent natural frequency (pressure transducer), the two waveforms if having the same natural frequency, will superimpose and the system will begin to oscillate at its maximum amplitude. This phenomenon is known as resonance.

If natural frequency of a system lies closer to the frequency of any of the sine wave components of arterial waveform, the system will resonate (resulting in excessive amplification of signal) and lead to an erroneously elevated systolic blood pressure and a lower diastolic blood pressure.

An accurate display of the arterial pressure waveform (for heart rates up to 180/min) can be ascertained, if natural frequency of the system is well above 24 Hz because amplitude of the higher harmonics above this frequency is so small that the impact of resonance is clinically insignificant.

The natural frequency of a system is determined by the formula:

$$[f_n = r/2.\sqrt{S/\pi\rho L}]$$

where f_n is natural frequency of the system, r is radius of tubing, S is stiffness of the tubing, ρ is density of fluid, and L is length of the fluid column.

Therefore, for maximizing the natural frequency of a measuring system, we need to use a short and wide catheter connected to a stiff and short piece of tubing.

The catheter-transducer system commonly used in the intensive care unit setting is an "underdamped, second-order dynamic system".[5]

Damping

Any process that resists vibrations or noise in an oscillating system will reduce the amplitude of oscillations in that system. This is known as damping.

Pressure monitoring systems are underdamped systems, showing some degree of pressure overshoot. Some amount of damping may therefore be essential, but excess (overdamping) or insufficient (underdamping) damping adversely affects the output. In an arterial pressure measuring system, damping is mostly from friction in the pathway of fluid column. However, many factors may lead to excessive damping like:

- Narrow, long or compliant tubing
- Kinks in cannula or tubing
- Three-way stopcocks
- Air bubbles
- Clots
- Vasospasm.

An underdamped system leads to erroneously high systolic blood pressure (SBP) and underestimation of diastolic blood pressure (DBP). On the contrary, overdamping results in under-reading of SBP and over-reading of DBP. However, the mean arterial pressure (MAP) is relatively unaffected in both the cases.

The optimal damping coefficient of a system depends upon its natural frequency. In a system with very low natural frequency, no amount of damping can prevent distortion of the measured waveform by resonance. On the other hand, in a system with very high natural frequency, the waveform is unaffected by resonance (within clinically relevant range of frequencies), thereby displaying an adequate dynamic response even at wide latitudes of damping coefficients.

Fast Flush Test

Fast flush test is used to determine the natural frequency and damping coefficient of a measuring system. In this test, the system is flushed with a high-pressure saline (at around 300 mm Hg) for a brief period of time and then the flush is suddenly released. After releasing the flush, arterial trace shows a number of oscillations before true pressure trace is attained. Thereafter, amplitude ratio of two consecutive resonant waves is calculated (ratio of amplitude of second oscillation wave to that of the first oscillation wave) and corresponding damping coefficient is calculated from a table. Amplitude ratio shows how quickly the system comes to rest. Depending upon the damping coefficient, system can be classified into:[3]

- *Underdamped system (damping coefficient <0.6)*: There is an overshoot and several oscillations before the arterial pressure trace.
- *Optimally damped system (damping coefficient = 0.64)*: Minimal overshoot and no oscillations occur before the arterial pressure trace.
- *Critically damped system (damping coefficient = 1)*: Precisely measured pressure change with no overshoot or oscillations but the system may take a longer time to attain new pressure. It is the minimal amount of damping required to prevent any overshoot.

- *Overdamped system (damping coefficient >1)*: The system is very slow to respond and the full extent of pressure change may be very delayed.

To calculate natural frequency of the system (f_n), paper speed (in mm/sec) is divided by the distance between two consecutive oscillations (in mm).

COMMON SOURCES OF ERROR AND COMPLICATIONS[6]

The most frequent error associated with pressure transducer is due to the misuse of equipment and misinterpretation of data. Failure to level the transducer to reference point will result in measurement error as a result of hydrostatic pressure. Every 10 cm change in height from the leveling point, will result in 7.5 mm Hg change in pressure (or 10 cm of water) which may lead to minute increase in blood pressure, however if we are measuring central venous pressure (CVP) or intracranial pressure (ICP) this may lead to significant error as the later pressures (CVP, ICP) are normally low. The system should also be adequately zeroed before measuring intravascular pressures.

The other sources of error could be due to kinking or occlusion of the catheter or tubing and due to underdamping or overdamping of the pressure waveform. Comparison of the pressure tracing with patient's plethysmographic waveform and electrocardiogram may also help in ruling out the possible artifacts.

Pertaining to the arterial catheter which points upstream, where the blood flows toward the catheter and thus, when this blood is suddenly stopped by the tip of the catheter, the kinetic energy of the blood is partially converted into pressure. This converted pressure may slightly increase (2–10 mm Hg) the SBP measured by an intra-arterial monitoring system. This phenomenon of erroneous augmentation of directly monitored systolic pressure is known as the end-hole artifact or the end-pressure product. This can be minimized using the catheter that has largest possible diameter (with respect to vessel) but smallest length.

All tubing connections should be tightly secured and stopcocks properly closed and placed in visible locations to prevent the dangerous complications of hemorrhage or venous air embolism.

Pressure transducer connected to arterial cannula poses an additional risk of accidental injection of intra-arterial medications and flushing of air directly into the arterial circulation.

Finally, use of an indwelling catheter may be associated with bloodstream infection.[7,8] Pressure transducers have also been associated with transmission of pathogens and infection control guidelines should be strictly adhered to while dealing with the transducers.

Additionally, central and arterial line insertion and maintenance may also cause mechanical (pneumothorax, arrhythmia, catheter or guidewire embolization) and thrombotic (usually in long term use) complications, however detailed discussion of these complications is beyond the scope of this chapter.

TRANSDUCER DEVELOPMENT

Over last several decades, pressure transducer development has focused on increasing accuracy, miniaturization, and reducing production cost. Several newer types of transducers have been developed:

- *Piezoresistive sensors*: Piezoresistive sensors use crystal semiconductors (e.g. silicon). Mechanical strain changes the crystalline structure of semiconductors, which affects electrical resistance of the material. The silicon sensor is less prone to drift and has three times the tensile strength of a steel wire but it is susceptible to errors due to changes in temperature.
- *Capacitative sensors*: Capacitative sensors are based on parallel plate capacitors, where one plate of the capacitor is a metal or metal-coated diaphragm. Deflection of diaphragm under pressure increases the capacitance by reducing gap between the plates. They are the most precise sensors and are less prone to temperature errors. However, the size is larger and they are more expensive than piezoelectric sensors.

SUMMARY

Transducer is a device that changes the energy from one form into another form. Pressure transducer is an extremely useful clinical tool and provides a detailed analysis of the patient's cardiovascular system when used judiciously with other components of the pressure monitoring system. Knowing the basic principles of its functioning can help us detect and prevent the common sources of error, which is essential to ensure that a precise measurement is made.

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Workbook on Hemodynamic Management

Salient Features

- 10 world-class experts in the field of hemodynamic management have written clinically-oriented chapters especially for this workbook
- 22 other chapters are written by Indian experts which cover all the aspects of Hemodynamic Management
- The focus of this book is not merely on monitoring aspects but as the name of the workbook goes, there is a significant emphasis on management aspects and clinical decision making
- A "Must Read Workbook" for trainees and young doctors in Intensive Care Medicine as well as a valuable guide for practicing intensivists.

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