Principles of pressure transducer function and sources of error in clinical use

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Abstract

The invasive measurement of physiological pressures is a common requirement in anaesthesia and intensive care medicine. From arterial blood pressure to intracranial pressure, these calculated variables give a swift graphical and numerical representation of a patient's current physiological status. This allows us to respond rapidly to conditions outside our preferred parameters and to carefully titrate treatments to target effects. These systems are, however, not infallible. An understanding of the principles of their function will promote appropriate use and an ability to recognize and react to sources of error. This article aims to furnish the reader with this level of understanding in order to inform their academic and clinical practice.

Keywords Calibration; damping; drift; energy; force; harmonics; natural frequency; pressure; strain gauge; Wheatstone bridge

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Pressure, force and area

Pressure (P) is the force (F) exerted on an object by something in contact with it. It is defined as force per unit area (A):

$$P = F/A$$

Force is the physical ability to cause a change in the velocity of an object with mass (m) – i.e. acceleration (a). This is given by Newton's second law of motion: $F = ma$. Force is measured in Newtons (N). Area is measured in square metres (m^2); therefore pressure can be measured in N/m^2. The SI unit of pressure is the Pascal (Pa), which is equal to one N/m^2. Numerous other units of pressure are seen in anaesthetic practice and often relate to the original methods of pressure measurement:

- Liquid manometry – pressure is given as the height of the column of a given liquid and is equal to the product of column height, liquid density and gravitational force. This gives rise to cmH_2O, mmHg. Seen in mercury sphygmomanometers.
- Aneroid gauge – literally 'without air', a method of measurement reliant on the deforming properties of gas pressure on a system, e.g. Bourdon gauge – a coiled tube which is flattened out at higher pressures, manipulating a needle on a measurement dial. Seen on gas cylinders. Absolute pressure is the sum of the gauge pressure and atmospheric pressure.[1]

Learning objectives

After reading this article, you should be able to:

- define pressure and force in physical terms
- list commonly measured pressures that may require a transducer in anaesthetic practice
- draw a model of the components of an invasive arterial pressure measurement system and describe the ideal properties of each component
- explain the principles of the strain gauge and illustrate a Wheatstone bridge circuit
- outline the concepts of natural frequency, harmonics and Fourier analysis
- discuss the common sources of error in monitoring devices, how these are classified and what can be done to minimize their impact

Pressure measurement in anaesthesia

It is common (and often mandated) to measure certain biological pressures during anaesthesia and critical care admissions. Whilst non-invasive techniques, e.g. for the measurement of blood pressure, are sufficient in many cases, it is sometimes necessary to invasively monitor physiological pressure variables, commonly including:

- airway pressures
- non-invasive blood pressure
- invasive arterial pressure
- central venous pressure
- pulmonary arterial pressure
- intracranial pressure
- intra-abdominal pressure
- limb compartment pressure
- endotracheal tube cuff pressure
- uterine pressure/contraction as tocodynamometer component of cardiotocography.

Invasive arterial pressure measurement serves as a good example to illustrate the function of pressure transducers and the sources of error in their clinical use.[1,2]

Blood pressure measurement

Blood pressure is the force exerted by blood on the walls of the vessels which contain it. It has two components:

- static component consisting of the volume, mass and density of the blood
- dynamic component from the pulsatile nature of blood flow.

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Blood pressure is often formulaically represented as the product of cardiac output and systemic vascular resistance. It is the complex interplay between the contractility of the ventricles and the resistance to flow brought about by blood viscosity and vessel wall calibre. Furthermore, systolic, diastolic and mean arterial pressure elements can all be determined to varying degrees of accuracy by invasive and non-invasive techniques. It is no surprise, then, that the waveform produced during invasive arterial pressure monitoring is complex in itself and can be employed to derive much useful information about a patient's cardiovascular status.[1]

Transducers

A transducer is a device which converts energy from one form into another. Examples include:

- microphones (sound to electrical energy)
- radio antennae (radio waves to electrical energy)
- audio speakers (electrical energy to sound)
- solar panels (light energy to electrical energy).

The electromanometer measures invasive pressures by use of a pressure transducer. This converts mechanical energy to electrical energy, allowing an electrical signal to be transmitted to a processing unit before being displayed numerically or graphically for interpretation by the user. The method of converting mechanical to electrical energy is via a strain gauge. This gauge can sit at the tip of a catheter situated in a vessel or space whose pressure is to be measured. For example, the intracranial pressure monitors ('bolts') employed in neurosurgery consist of a strain gauge tipped catheter attached to a display box. Once this catheter is inserted, it is not possible to recalibrate the system as the gauge is intracranial. Errors in its function therefore require complete revision. It is possible to use a similar arrangement for intravascular devices, but more commonly the transducers are situated externally allowing easy access. This can be demonstrated when we examine the structure of an invasive arterial pressure set.

The main components shown in Figure 1 are:

- A: fluid bag under pressure of 300 mmHg, usually saline or heparinized saline
- B: pressure transducer with strain gauge
- C: flush mechanism to allow manual flush of catheter (constant 3–4 ml/hour fluid flushes the catheter to prevent thrombus formation and blockage)
- D: three-way tap to allow access for aspiration of blood from catheter and manual flush with syringe
- E: fluid filled line connecting cannula to transducer
- F: arterial cannula
- G: wire transmitting transducer signal to processing unit
- H: display module to numerically and graphically represent the processed signal.

As will be explored later, errors can occur anywhere along this system.[1–3]

Strain gauge and Wheatstone bridge

The continuous column of fluid in this system means that the arterial pressure waveform can be transmitted to the external transducer relatively unchanged. The fluid column reaches a flexible diaphragm which interfaces with the transducer unit. This diaphragm is displaced by oscillations in the fluid column caused by changes in arterial pressure. The adjacent strain gauge is, in turn, distorted by the movement of the diaphragm. Distortion of the resistor wires of the gauge causes a change in their resistance.

Resistance is a measure of the difficulty of passing an electrical current through an object. According to Ohm's Law, the potential difference (or voltage (V)) across a conductor is proportional to the current (I) passing through it:

$$V \propto I$$

The constant of proportionality used to produce the familiar equation is resistance (R)

$$V = IR$$

Therefore:

$$R = V/I$$

The equipment required to measure invasive arterial pressures

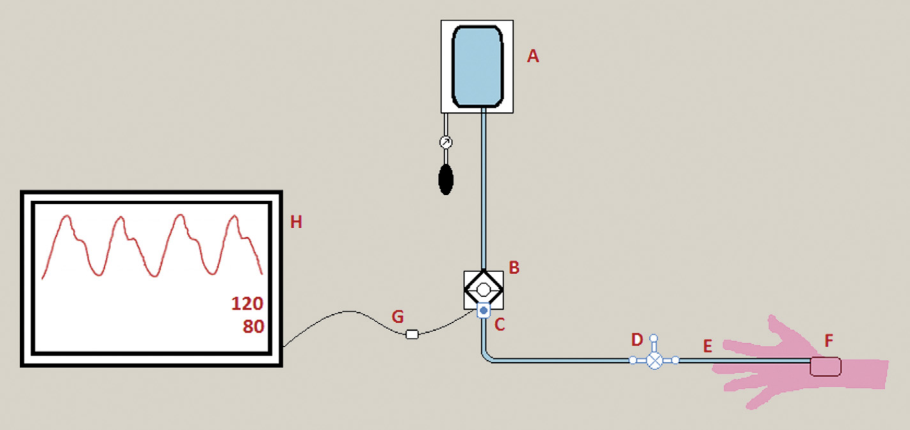

Figure 1

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