Principles of pressure transducers, resonance, damping and frequency response

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Abstract

The most common invasive pressure transducer we use is a strain gauge. This consists of short pieces of wire attached to a diaphragm which is distorted during transmission of the pressure impulse. Consequent changes in the length of the wire alter their resistance, which, when connected to a Wheatstone bridge circuit, allow us to produce an electrical signal for display. Resonance may occur when the frequency of the pressure waves in the incoming impulse matches the natural frequency of the transducer thereby causing superimposition of pressure waves. The natural frequency of the system may be increased by using a stiff diaphragm and short wide-bore tubing. Fourier analysis allows us to breakdown a complex waveform into its component harmonics. Faithful reproduction of the waveform is possible using the first ten harmonics. Therefore a transducer system with a natural frequency response of 30 Hz would allow us to reproduce pressure waves of 180 beats/min. Damping reduces the high-frequency noise to allow a more accurate reproduction of the wave form. Too little damping allows oscillations which distort the results while too much damping delays the signal.

Keywords damping; frequency; invasive; resonance; transducer; Wheatstone bridge

When measuring pressure in anaesthesia we commonly wish to measure arterial, venous or pulmonary pressures. In addition, we may wish to measure intracranial pressure. These pressures consist of a hydrostatic component caused by the ‘weight’ of fluid within the vessel (in addition to any externally generated pressure within an enclosed space, e.g. intracranial pressure) and a kinetic, pulsatile component due to the contraction of the heart propelling the blood forward.

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Transducers convert one form of energy to another. Solar panels, wind turbines and wave machines are all examples of transducers. We therefore need a transducer which can sense the physiological pressure signals and convert their energy into an electrical signal to be amplified and displayed on a screen for analysis. Such a device will need an accurate system for transmission of the pressure wave from sensor to transducer and an accurate transducer for the faithful reproduction of the wave as an electrical signal.

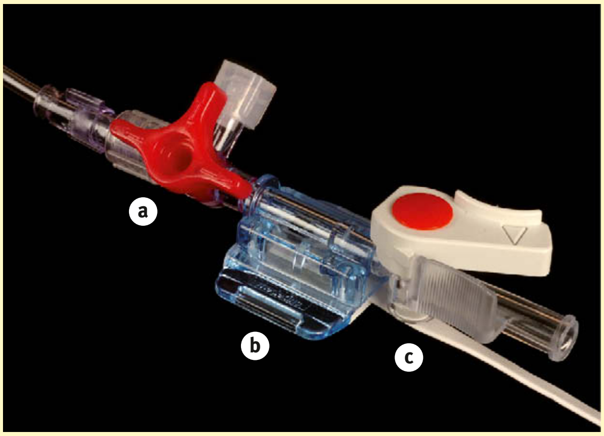
Two types of transducers are currently available. The first has the sensor on a catheter tip placed directly within the vessel. Clearly, these would be the most accurate but they are expensive, prone to thrombin deposition and cannot be recalibrated once *in situ*. Consequently, they are not commonly used in clinical practice.

More commonly, therefore, we use a transducer connected to the pressure source by a catheter and tubing filled with fluid. The design and components involved are vital to the accurate function of the overall system. We shall see that the ideal design for this system is to use a short wide-bore catheter inserted into the vessel, connected to straight stiff tubing to reduce the effect of damping. In addition, we need to minimize the number of taps and angles exposed to the fluid column and ensure no air is present in the tubing system. Ultimately, the aim is to reduce the degree of resonance and damping to achieve as accurate a representation of the original pressure wave as possible.

The transducer

The commonest transducer used to convert mechanical energy into an electrical signal is a strain gauge (Figure 1). This consists of short lengths of wire bonded to a diaphragm. The diaphragm is in contact with the fluid column leading from the arterial cannula to the transducer. Distortion of the diaphragm by the transmitted arterial pressure wave will alter the length of the wires attached to it. As the length of the wire increases (and

Disposable pressure transducer set



a Fluid-filled tubing connecting the transducer to the pressure source. **b** Transducer attached to the tubing from the patient and the electrical wire leading to the monitor. **c** Flush valve attached to the pressurized giving set

Figure 1

diameter decreases) its resistance will increase (and vice versa). Such resistance changes can be detected by a Wheatstone bridge (Figure 2) and converted into an electrical signal for display.

Most current transducers use two or more lengths of wire. This design allows one wire to lengthen while one shortens, thereby increasing the sensitivity and accuracy of the device. Remember that the distortion of the diaphragm may be very small indeed. In addition, one wire may be isolated from external strain to compensate for the effect of temperature.

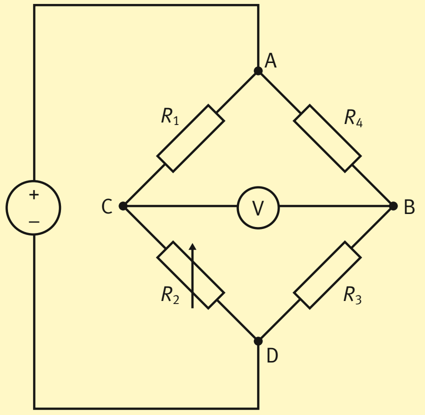
Practical use of the transducer

Before use, the transducer must be connected to the appropriate tubing to allow an accurate transmission of the pressure waveform from the vessel to the transducer. This must be designed to minimize the chance of resonance or damping (see below). In addition, the transducer must be connected to an electrical wire to carry the output signal to the monitor for processing and display.

Once connected to the monitor, the transducer must be zeroed by exposing it to atmospheric pressure. This point is usually taken at the midpoint of the heart. The transducer will then measure all pressures with reference to atmospheric pressure. If large and unexpected changes in pressure occur over time this may be due to baseline drift in the transducer and the zero should be repeated. Calibration to a known constant pressure, in addition to atmospheric pressure, is now not required owing to the greater accuracy of modern transducers.

Finally, the transducer must be placed at the level of the heart. This is best achieved in the supine patient at the mid-chest level. Perhaps of greater importance than the actual position is to ensure that all readings are then taken from the same place, particularly when measuring low-pressure systems such as central venous pressure.

Wheatstone bridge



The change in resistance in the strain gauge can be measured using a Wheatstone bridge. In the diagram, if R1= R4 & R2 = R3 then the appplied voltage will be equally divided between each limb of the circuit and no potential difference will exist between B and C. Let us now substitute our strain gauge for R3 and a variable resistor for R2. If this resistance is adjusted so that no potential difference exists between B and C we can assess the resistance of our strain gauge at R3. More commonly today we use 2 or more lengths of wire on the diaphragm positioned such that when one is stretched the other shortens, thereby increasing its sensitivity.

Figure 2

Remember, however, that every 10 cm change in height will result in a 7.5 mm Hg change in pressure. This is important when patients are in the sitting position when an acceptable pressure at the level of the heart may result in a low pressure in the cerebral circulation.

Resonance

Every system or object has a natural frequency. For a simple object this is the frequency at which it vibrates with maximal amplitude and represents the lowest harmonic of its harmonic series. This frequency is the inverse of the wave length ($v = f\lambda$, where v is the velocity of a wave, f is the frequency and λ is the wavelength). The size, shape and materials from which an object is made affect this natural frequency.

Resonance occurs when a second energy source is introduced into an object or system with a frequency at or near its natural frequency. In the case of our pressure transducers a second waveform (arterial pressure wave) is introduced to a system with its own inherent natural frequency (the transducer system). If the two waveforms are of similar frequency, they will ‘superimpose’ onto each other with the resulting waveform showing greater amplitude in its peaks and troughs. (Imagine pushing a child’s swing. If the frequency of the ‘push’ is in phase with the natural oscillation of the swing the amplitude of the swing will increase.) In addition, as the second wavefront passes through the object some of the energy will be reflected back to the original entry point. Again, if the frequency of the reflected wave is equal to the natural frequency of the object, and they are in phase with subsequent waves, the two waves will then constructively interfere. The amplitude of the resulting wave will be greater than either of the original waves. The system will then resonate. This natural frequency, therefore, is often also known as the resonant frequency.

If the secondary energy source has a natural frequency well above or below the object’s natural frequency then the wave will be transmitted largely unaffected. These high-frequency waves will have a very low amplitude and so have little effect on the original waveform. (Again, imagine a swing. If the driving ‘push’ is very much faster than the natural oscillation of the swing it will have little effect on the amplitude of the swing.)

This phenomenon may be important in engineering. In 1940, the Tacoma Narrows Bridge collapsed shortly after it opened. This happened not because the bridge was badly built, but because, at a certain speed, wind passing under the bridge caused vibrations at its natural frequency, which set up resonance, and the bridge began to vibrate more and more forcibly until it collapsed. Similarly, if an opera singer can maintain a note at the exact natural frequency of a wine glass it will resonate until the vibrations are large enough to shatter the glass.

The relevance of resonance to invasive blood pressure monitoring is that, if the transducer system has a resonant frequency near to that required for reproduction of the blood pressure waveform, then resonance will make the system overestimate systolic pressure and underestimate diastolic pressure.