

Biological Signals and their Measurement

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INTRODUCTION

Biological signals are electrical or magnetic signals generated by biological activity within the human body. They can be monitored directly using electrodes, for example the electrocardiogram (ECG) and electroencephalogram (EEG), or can be reproduced via a system incorporating a transducer, for example invasive blood pressure monitoring. The signals are amplified, manipulated, processed and then usually analysed by a computer. The end product is the biological signal converted into a readable form.

SYSTEMS MEASURING ELECTRICAL SIGNALS

Electrodes

An electrode is a solid electrical conductor through which an electrical current can enter or leave a medium, for example the human body. They are usually in direct contact with a tissue. Skin electrodes are usually silver metal coated in a thin layer of silver chloride, in contact with chloride gel on a spongy pad, which then comes into contact with skin.



Figure 1. Skin silver-silver chloride electrodes

THE ELECTROCARDIOGRAM (ECG)

This is the surface reflection of myocardial electrical activity. Electrical activity from the myocardium is measured as a voltage at a series of skin electrodes. The electrical potentials from the myocardium at the level of the myocyte are about 90mV, but by the time they have traversed the chest to reach the skin they are reduced to 1-2mV. Skin-electrode impedance also accounts for some of this reduction in voltage.

Impedance

Impedance is resistance to the flow of alternating current. The electrodes themselves create a small

amount of impedance due to the electrochemical properties of the electrode. Skin-electrode impedance is due to imperfect mechanical contact between the electrode and skin. If impedance is high, then the signal can be distorted by interference, often from the domestic mains supply or by muscle movement producing electrical activity in the muscle. To reduce skin resistance and improve the signal, the skin should be hairless, clean and dry.

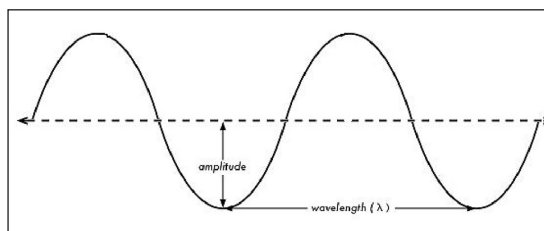


Figure 2. A typical sine wave. The frequency is the number of cycles, or complete sine waves, per second and the reciprocal of the wavelength. Hertz (Hz) is the standard unit of frequency

Sine waves

The ECG signal is actually a complex waveform made up of many different sine waves superimposed onto each other (Figure 2). A sine waveform is a description of a quantity that varies rhythmically with time. An example is the variation of voltage against time of an alternating current. Fourier analysis can be used to break down complex biological waveforms into their constituent individual sine waves. The slowest individual sine wave of the waveform is known as the *fundamental frequency*. Related sine waves that are multiples of the fundamental frequency are called the *harmonics*.

Bandwith and amplification

Since the amplitude (or 'strength') of these types of biological signals is very small, they need to be *amplified* in order to be interpreted. Amplification describes the process of strengthening a signal, so that it usable. During the amplification process, the frequency range of amplification (the *bandwidth*) must be sufficient to ensure that sufficient numbers of the *harmonics* of the signal are amplified, such that the amplified signal accurately represents the original unamplified signal. To

Summary

Biological signals are electrical or magnetic activity within the human body. They are usually detected via electrodes or transducers. Complex waveforms are reproduced using Fourier analysis. Transducers convert one energy form into another and can be used to monitor biological signals, for example blood pressure.

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be able to accurately reproduce the initial waveform, the bandwidth needs to be wide enough to include the fundamental and (usually) eight further harmonics.

The bandwidth for ECG amplification is 0.5-80Hz. A lower range would allow interference from movement and respiration, whereas higher frequencies would detect and amplify muscle movement and distortion from nearby equipment. For monitoring purposes the bandwidth can be reduced to 40Hz, which removes interference from mains current, but needs to be increased for ST segment analysis.

The ECG display

The ECG is displayed via an oscilloscope, usually moving at 25 mm.s⁻¹, or as a digital image with the same speed on the baseline. Depolarisation towards a lead causes a positive deflection and away from a lead causes a negative deflection (Figure 3). The size of the deflection is usually proportional to heart muscle bulk underlying that electrode.

Usually, for diagnostic purposes, ten electrodes are applied to the skin, one on each limb (the 'limb leads') and six across the anterior chest wall (the 'chest leads'). This arrangement gives twelve different waveform readings, the '12-lead ECG'.

The augmented unipolar and chest leads use a reference electrode by connecting all three augmented unipolar leads.

During anaesthesia, it is common to only use the three standard leads, with lead II being superior for detection of arrhythmias. Other configurations of electrodes include 'CM5', which is better at detecting left ventricular ischaemia. The right arm electrode is placed on the manubrium, the left arm at V5 position and the third lead on the left shoulder.

THE ELECTROMYOGRAM (EMG)

The EMG is used to measure spontaneous or evoked potentials from muscles. Needle electrodes can be inserted into the muscles or surface electrodes can be used. The patient can either carry out a movement to

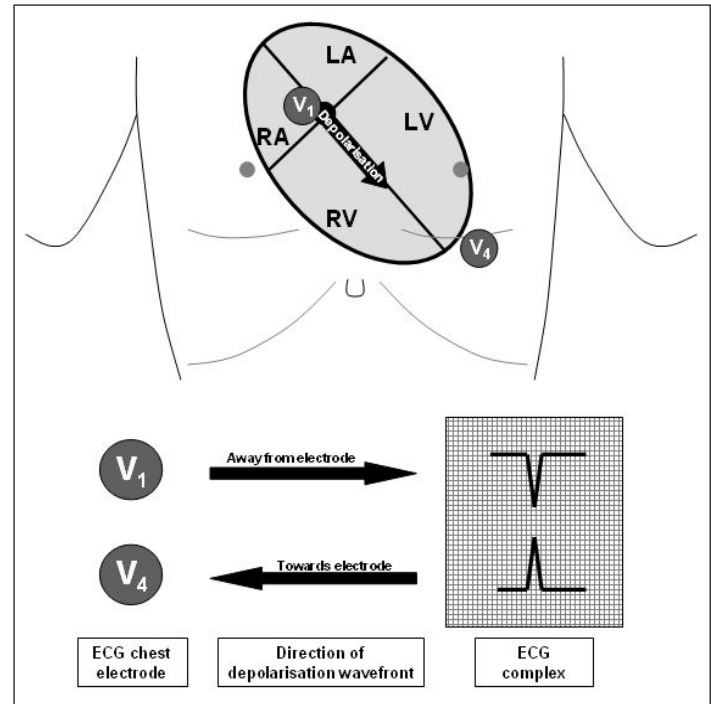


Figure 3. Diagram to show how electrode position determines the polarity of the ECG trace during depolarisation of the heart muscle (here depolarisation travelling from the AV node through the interventricular septum towards the apex of the heart). Lead V1 is over the right fourth intercostal space and lead V2 is over the apex of the heart

elicit a spontaneous potential, or the nerve supplying the muscle can be stimulated. The measured potentials range from less than 50mV up to 20-30mV. The bandwidth of the amplified signal is much larger than the ECG, with a range of 0-4kHz.

Clinically, the principle of the EMG can be used for monitoring neuromuscular blocking drugs. A nerve stimulator is used to apply a supramaximal current to a nerve to ensure depolarisation. The

Table 1. Standard lead positions. The chest leads are positioned as indicated. The standard and augmented unipolar leads are derived from the readings of four leads attached to the patient's limbs

Standard leads	I	Between right and left arm
	II	Between left leg and right arm
	III	Between left leg and left arm
Augmented unipolar leads	aVR	Right arm
	aVL	Left arm
	aVF	Left leg
Unipolar chest leads	V1	Right parasternal, 4th intercostal space
	V2	Left parasternal, 4th intercostal space
	V3	Between V2 and V4
	V4	Over apex
	V5	At level of V4 in anterior axillary line
	V6	At level of V4 in mid-axillary line

muscle response is commonly detected visually, but it can be detected electrically and more accurately by EMG. EMG is also used for nerve conduction studies to diagnose myopathic and neuropathic disorders, which patients in the intensive care unit may develop.

THE ELECTROENCEPHALOGRAM (EEG)

The EEG measures the electrical activity of the brain using skin electrodes. Monitoring brain activity usually uses 21 electrodes for diagnostic purposes in the internationally recognised '10-20 system'. The EEG detects the sum of post-synaptic potentials from the pyramidal cells in the cerebral cortex in response to rhythmic discharges from thalamic cells.

The EEG waveforms vary with frequencies ranging up to 40Hz. The amplitude of the waveforms can be between 1 and 100mV. The frequencies are often divided into bands:

- Alpha: 8-13Hz
- Beta: 13-40Hz
- Theta: 4-7Hz
- Delta: <4Hz

All the frequency bands can be normal in some situations but pathological in others. For example, alpha rhythms are seen during rest with the eyes closed, especially over the parieto-occipital region (Figure 4), but are also seen in coma where they represent deactivation. Delta bands can be a sign of an intracranial lesion, but are normal in babies.

The EEG has a number of clinical applications and is useful in the Intensive Care Unit (ICU) to diagnose seizure activity, particularly when the clinical picture is unclear (for example in 'non-convulsive status epilepticus'). Anaesthetic drugs affect the EEG. As the level of anaesthesia increases, the frequency of the EEG waveforms decreases dose-dependently until, at very high doses, the frequencies are very low, with suppressed amplitude and occasional bursts of higher frequencies with high amplitudes. *Burst suppression* is when there are absences of these high frequency episodes and is taken as the desired end-point to minimise the cerebral metabolic rate, when treating patients in the ICU with intractable intracranial hypertension. Smaller doses can cause an increase in frequency and activity, with mainly beta bands detected.

During clinical anaesthesia the picture may be complicated by other conditions that alter brain activity, for instance hypoxia and hypercarbia. In addition, different anaesthetic drugs produce different EEG characteristics.

BISPECTRAL INDEX MONITORING (BIS)

Full EEG monitoring is impractical in theatre and bispectral (BIS) index monitoring has superseded other methods for monitoring depth of anaesthesia. The EEG signal can be modified and an algorithm used to generate a number that represents a level of consciousness between 0 (very deep) and 100 (fully awake). BIS has been validated on healthy volunteers and different patient groups but there is no gold standard for comparison. A single pair of electrodes is applied to the patient's forehead as in Figure 5.

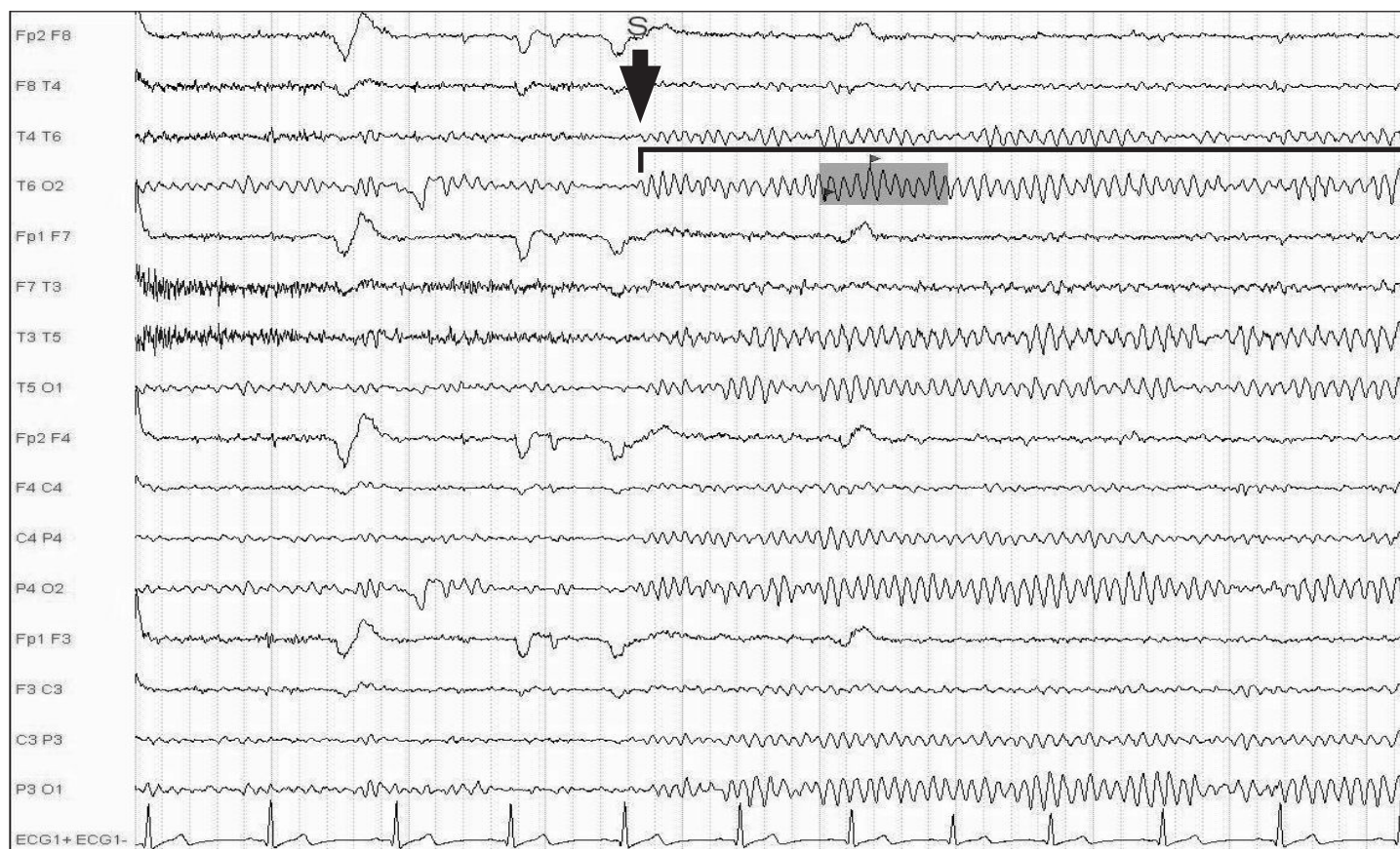


Figure 4. A normal EEG. The arrow indicates when the patient's eyes are closed and alpha rhythms (bracketed) are seen



Figure 5. Electrode positions for bispectral index monitoring (BIS)

The BIS index algorithm uses power spectral analysis and time-domain analysis. It also examines the relationship between the individual frequency components to each other (phase coupling). Time-domain analysis was developed as part of a ‘cerebral function monitor’ in the 1950s in order to measure changes in amplitude and frequency of brain signals over time. Power spectral analysis uses frequency-domain analysis, where wave amplitudes are measured and taken as an indication of ‘power’ within each frequency of the EEG. Power is plotted versus frequency, and each frequency is considered individually.

Table 2. Suggested interpretation of BIS values

BIS value	Interpretation
100-85	Awake, aware and capable of recall
85-60	Increasing sedation but rousable in response to stimulation
60-40	Surgical anaesthesia with decreasing probability of post-operative recall
40-0	Increasing incidence of burst suppression
0	Cortical electrical silence

BIS is thought to be independent of the anaesthetic drug given and correlates with clinical assessment of consciousness. One major disadvantage of BIS is that effects on consciousness due to opioids, ketamine and nitrous oxide are not reflected in BIS values. It is thought that the probability of post-operative recall is low if the BIS value is less than 60 intraoperatively. Studies have demonstrated that BIS monitoring intraoperatively reduces the risk of post-operative recall (as does the use of a volatile agent in the range 0.7-1.3 MAC in the presence of nitrous oxide).

SYSTEMS INCORPORATING A TRANSDUCER

Transducers convert one form of energy into another. With biological signals, transducers convert physiological signals into electrical signals, which can be then interpreted.

INVASIVE BLOOD PRESSURE (IBP) MEASUREMENT

Components and principles of IBP monitoring

The components of an intra-arterial monitoring system can be considered in three main parts (see Figure 6):

1. The measuring apparatus,
2. The transducer,
3. The monitor.

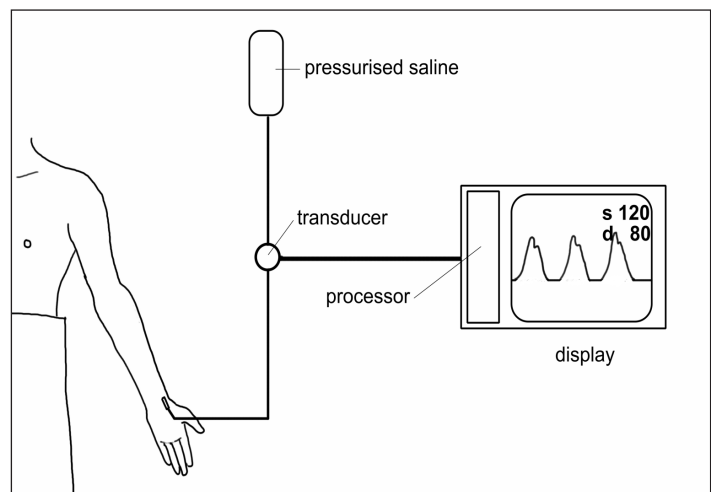


Figure 6. Components of an arterial monitoring system

The measuring apparatus

The measuring apparatus consists of an arterial cannula (20G in adults and 22G in children) connected to tubing containing a continuous column of saline that conducts the pressure wave to the transducer. The arterial line is also connected to a flushing system consisting of a 500ml bag of saline pressurised to 300 mmHg via a flushing device. Formerly 500IU heparin was added to this fluid, but many centres now consider this to be unnecessary. The flush system provides a slow but continuous flow to the system at a rate of approximately 4-5ml per hour. A rapid flush can be delivered by manually opening the flush valve. There is also usually a 3-way tap to allow for arterial blood sampling and the ejection of air from the system if necessary. The three-way tap must be clearly labelled as arterial to avoid the inadvertent intra-arterial injection of drugs. For small children a smaller volume of flush is administered via a syringe driver, so that it is not possible to over-administer fluid by repeated flushing of the arterial cannula.

The transducer

A transducer is any device that converts one form of energy to another – for example, the larynx is a type of physiological transducer (air flow is converted to sound). The output of transducers is usually in the form of electrical energy. In the case of intra-arterial monitoring the transducer consists of a flexible diaphragm with an electric current applied across it (Figure 7). As pressure is applied to the diaphragm it stretches and its resistance changes, altering the electrical output from the system. The transducers used are differential pressure transducers and so must be calibrated relative to atmospheric pressure before use.

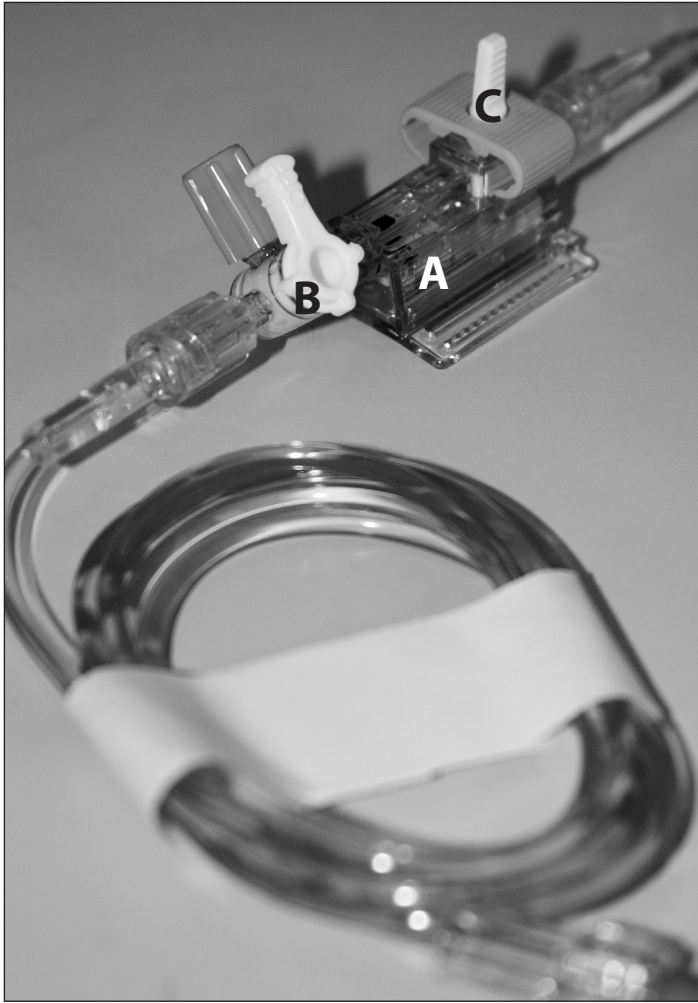


Figure 7. The transducer (A) of an arterial monitoring system, with a three way tap (B) for zeroing against atmospheric pressure and flushing device (C)

The monitor

It is not necessary for the anaesthetist to have an in-depth understanding of the internal workings of the monitor. Modern monitors *amplify* the input signal; amplification makes the signal stronger. They also *filter* the 'noise' from the signal – unwanted background signal is removed with an electronic filter - and display the arterial waveform in 'real time' on a screen. They also give a digital display of systolic, diastolic and mean blood pressure. Most monitors incorporate various safety features such as high and low mean blood pressure alarms and tachycardia and bradycardia alerts.

Accuracy of IBP monitoring

The accuracy of intra-arterial monitoring is affected by several important physical principles - the *oscillation*, *natural frequency*, *damping* and *resonance* of the system

Oscillation

A swinging pendulum is an example of a system that oscillates. When a pendulum is pushed (energy is put into the system), it moves away from its resting position, then returns to it. The resting position for a pendulum is at the bottom of its arc of swing and is dictated by gravity.

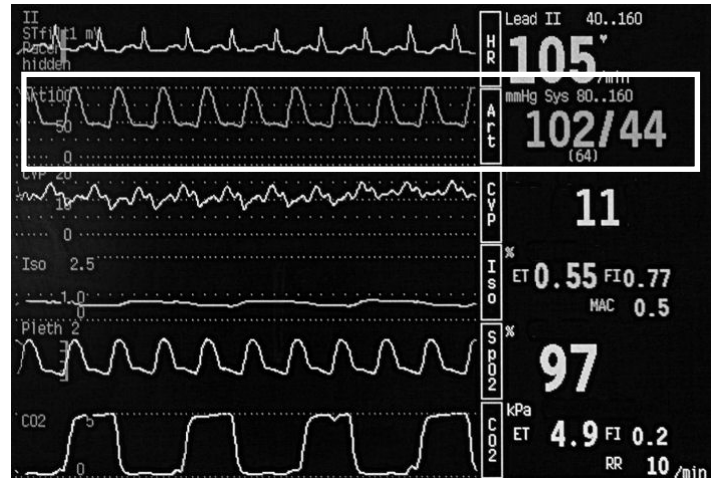


Figure 8. Invasive blood pressure monitoring (boxed). The waveforms are usually colour coded (red for the arterial trace) and the monitor displays the systolic/diastolic BP, with the mean arterial BP in brackets below

However, the pendulum doesn't usually just return to the resting position, but tends to overshoot, swinging past the resting point in the opposite direction to the original push. This cycle continues until all the energy put into the system has been dissipated. The tendency of a system to move either side of set point is referred to as its tendency to *oscillate*.

Damping

Imagine you have two identical pendulums. One has recently been well greased at its point of rotation (fulcrum) and the other is stiff from rust. When an equal sized force is applied to each, the well greased one will oscillate freely around the set point but the old rusty pendulum may barely move. This is because much of the energy put into the system will be used up or 'damped' in overcoming the frictional force of the rusty axis. The rusty pendulum will tend to oscillate at smaller amplitude (i.e. smaller swings) and for a shorter period of time than the well greased one. How freely a system oscillates following an input of energy depends on the degree of *damping* in the system.

A 'well damped' system tends not to oscillate freely whereas a 'poorly damped' system may oscillate wildly. The amount of damping inherent in a system can be described by the *damping coefficient (D)*, which usually lies between 0 and 1 (but can be greater than 1). A system with a D value greater than 1 describes a system that is over-damped, will not oscillate freely, that takes a long time to initially move away from and to return to its resting point, but does not oscillate (a high friction pendulum). A D value less than 1 and approaching 0 describes a system that is under-damped, that oscillates freely, moving rapidly away from its resting point and back again, but tends to overshoot and then oscillate around the resting point (a low friction pendulum). A D value of exactly 1 is known as *critical damping*.

Oscillations are undesirable in physiological measuring systems. These systems require accurate measurement of a maximum amplitude (for instance, that caused by the arterial pulsation, the systolic blood pressure), with a rapid response time and rapid return to the set point, ready for the next measurement. The ideal level of damping applied to a measuring system is a compromise between achieving a rapid response time and accurate reflection of maximum amplitude by designing a

system with D close to 0, and needing a system that returns to the resting point without excess oscillation (D around 1). In the case of an IBP monitoring system this would represent the difference between using very compliant measuring apparatus (compliant catheters, tubing) i.e. D approaches 0, and very stiff or non-compliant equipment i.e. D is closer to 1. The value of D chosen for physiological measuring systems such as IBP monitoring equipment lies between 0.6 and 0.7 – it is known as *optimal damping* (see Figure 9).

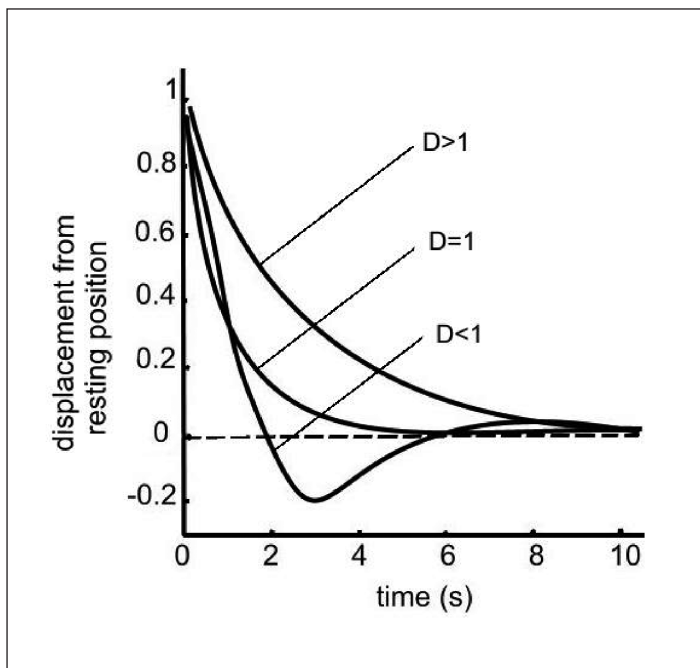


Figure 9. Graph showing the effect of different levels of damping on the oscillation of a measuring system

Natural frequency and resonance

A pendulum of set length and with a set weight at the end will always oscillate at exactly the same frequency, no matter what the initial starting point of the oscillation. In other words, whether you give the

pendulum a small push or a really hard shove it will make the same number of oscillations per unit time (although the amplitude of the oscillations will differ). This is why pendulums can be used to keep time. Any system such as this will have a frequency at which it 'naturally' oscillates. This frequency is known as the *natural frequency*.

If the input of energy into a system is occurring at the same frequency (or close to) the natural frequency, a phenomenon called *resonance* occurs and the output amplitude of the oscillations is greatly magnified. In the case of intra-arterial blood pressure monitoring this could lead to over-reading of the systolic blood pressure. Arterial pulsation is a complex sine wave and is composed of many individual sine waves. It is therefore important that the natural frequency of the measuring equipment (the catheter and column of saline etc) does not correspond to any of the component frequencies of the arterial pulsation input. This is achieved by making sure that the natural frequency of the measuring system is raised above any of the component frequencies of the arterial sine waveform.

The characteristics of the measuring equipment that will ensure that the natural frequency of the system is higher than that of the arterial pulsation are:

- Arterial catheter must be short and with the maximum gauge possible,
- Column of saline must be as short as possible,
- The catheter and tubing must be stiff walled,
- The transducer diaphragm must be as rigid as possible.

FURTHER READING

- Magee P and Tooley M. The physics, clinical measurement, and equipment of anaesthetic practice. *Oxford Medical Publications*.
- Davis P and Kenny G Basic physics and measurement in anaesthesia. Butterworth Heinemann. Whyte S and Booker P Monitoring depth of anaesthesia by EEG. *British Journal of Anaesthesia, CEPD Journal*; **2003**:106-110.