MEASUREMENT OF INTRAOCULAR PRESSURE

Here we will examine non-invasive measurement of intraocular (within the eye) pressure. Glaucoma - raised intraocular pressure - causes visual field constriction and ultimately blindness. Chronic glaucoma may not be noticed until the optic nerve is permanently damaged. The cause may be obstruction of the drainage of aqueous fluid from the anterior compartment of the eye. It is obviously important to know the normal range of intraocular pressure and to be able to measure it non-traumatically. Unfortunately, the only definition of 'normal' for intraocular pressure is the pressure that does not lead to glaucomatous damage of the optic nerve head.

Numerous large studies of intraocular pressure have been made. Normal pressure is about 15 mmHg, with a standard deviation of about 3 mmHg. Figure 1 shows the interpretation of the results as two populations (non-glaucoma and glaucoma) which overlap considerably. The standard deviation should also be treated with caution as the distributions are skewed. The figures suggest a normal range of approximately 10 - 20 mmHg. Intraocular pressure is influenced by a number of factors (blood pressure, drugs etc.) which are discussed in standard ophthalmology texts.

The problem, as far as we are concerned, is how we measure intraocular pressure non-invasively. The eye is a fluid-filled globe, and we can measure the pressure within it by relating the deformation of the globe to an externally applied force. Tonometers (devices for measuring the pressure within the eye) are of two types: indentation, which are no longer used, and applanation (flattening).

![Diagram of applanation tonometer](https://example.com/diagram.png)

Figure 2: Applanation tonometer applied to the cornea

![Graph of intraocular pressure distribution](https://example.com/graph.png)

Figure 1: Distribution of intraocular pressure for normal and glaucoma groups.
Applanation tonometers rely on the relationship between wall tension and pressure in an elastic sphere. The surface tension \( \gamma \) (gamma) is related to the pressure difference \( \Delta p \) across the curved wall by \( \Delta p = \frac{2\gamma}{r} \), where \( r \) is the radius. If the wall of the sphere is locally flattened (i.e. \( r = \infty \)), the pressure difference \( \Delta p \) will be zero, and the pressure within the sphere can be related to the force applied to the wall by

\[
\text{pressure} = \frac{\text{force}}{\text{area}}.
\]

Ophthalmologists give this latter expression the grandiose name of Maklakov-Fick or Imbert-Fick Law, but it is no more than the standard definition of pressure.

The assumptions are that the eye is a spherical shell, perfectly flexible, has an infinitely thin wall, and there are no surface tension effects due to fluids in contact with either surface of the wall. In practice, the eye violates all these assumptions (see anatomy of the eye). The cornea has a central thickness of approximately 0.55 mm (Figure 2), so that the outer contact area is less than the internal flattening. The wet surface gives a surface tension acting on the plunger, and a finite force is required to bend the cornea. Surface tension has a component acting in the same direction as the applied force, which is opposed by the bending force. In the literature, it is stated that it has been found empirically that these forces balance out when the contact area is 3.06 mm diameter. Given all the assumptions about the technique, and the wide range of intraocular pressures, this precision seems inappropriate. The resulting volume displacement is about 0.5 µl, compared to 180 µl for the volume of the anterior chamber and 60 µl for the posterior chamber, so that the applanation has a negligible effect on the intraocular pressure.

The Goldmann-type applanation tonometer applies a force to the surface of the cornea, and uses an optical system to determine when the applanated area is 3.06 mm in diameter. The cornea is anaesthetised with a topical anaesthetic, and the tear film is stained with sodium fluorescein. The meniscus surrounding the applanated area is visible because of the fluorescence, and is split into two semicircles by biprisms. The geometry is such that the inner edges of the semicircles touch when the area applanated is correct. The intraocular pressure can then be measured directly from a scale on the tonometer. Errors in the measurement can be due to variations in the thickness and curvature of the cornea (keratoconus/laser surgery), variations in tear film, age, epithelial oedema, time of day, blepharospasm/poor cooperation, posture, drugs and blood pressure/tight collar/neck-tie.

Tonometers are now available that use a puff of air to deform the surface of the cornea. By using a known velocity and volume of air, and measuring the resulting deformation of the corneal surface, it is possible to provide a reasonably accurate measurement of intraocular pressure in a much less invasive manner - convenient, but not a gold-standard.

A note on pressure:
The unit of pressure is the pascal (Pa), which is 1 newton per square metre (Nm\(^{-2}\)). A pressure given in pascals is more difficult to understand than the same pressure given in mm Hg, where the height of the corresponding column of mercury can be visualised:

\[1 \text{ mm Hg} = 133 \text{ Pa} = 0.133 \text{ kPa}\]

Sometimes the millibar is used as an alternative unit: 1 millibar = 100 Pa = 0.75 mmHg
PRINCIPLES OF MEASUREMENT

1.1 Transducers

A transducer is a device which can change one form of energy into another. A loudspeaker may be thought of as a transducer because it converts electrical energy into sound energy; an electric light bulb may be considered as transducing electrical energy into light energy. Transducers are the first essential component of almost every system of measurement. The simplest way to display a measurement is to convert it to an electrical signal which can then be used to drive a chart recorder or form the input to a computer. However, this requires a transducer to change the variable to be measured into an electrical signal.

A complete measurement system consists of a transducer, followed by some type of signal processing, and a display device.

![Diagram of measurement system]

**Fig 1**

1.1.1 Pressure Transducers

The unit of pressure is the pascal (Pa), which is 1 newton per square metre (Nm⁻²). A pressure given in pascals is more difficult to understand than the same pressure given in mmHg, where the height of the corresponding column of mercury can be visualised:

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Very often the greatest difficulty in making a physiological pressure measurement is getting access to the measurement site. The normal indirect method of measuring blood pressure is to use an inflatable cuff. If direct contact can be made to a fluid then it is possible to use a pressure transducer to record the pressure in the fluid. The most common physiological measurements of pressure are blood pressure, bladder pressure, and airways' pressure. The highest of these pressures is the arterial blood pressure which normally has a maximum during cardiac systole of 120 mmHg (16.0 kPa) and a minimum of 80 mmHg (10.6 kPa) during cardiac diastole. The lowest of these pressures is the airways' pressure which fluctuates by only 1 or 2 mmHg (0.13-0.26 kPa) during breathing. A fluid-filled system is used to measure blood pressure or bladder pressure whereas an air-filled system is used to measure airways' pressure.

The most common type of pressure transducer consists of a diaphragm, one side of which is open to the atmosphere and the other connected to the pressure which is to be measured. Pressure causes a proportional displacement of the diaphragm which can be measured in many ways. The most common method is to use strain gauges. A strain gauge is a device which measures deformation or strain. A single crystal of silicon with a
small amount of impurity will have an electrical resistance which changes with strain. If a silicon strain gauge is attached to the diaphragm of the pressure transducer then its resistance will change with the pressure applied to the diaphragm.

1.2 Electrodes

Before any electrophysiological signal can be recorded, it is necessary to make electrical contact with the body through an electrode. Electrodes are usually made of metal but this is not always the case, and indeed there can be considerable advantages in terms of reduced skin reaction and better recordings if non-metals are used. If we are to be accurate then we should regard an electrode as a transducer as it has to convert the ionic flow of current in the body to an electronic flow along a wire to a recorder.

1.2.3 Types of Electrode

There is no clear classification of electrodes but the following three groups include most of the commonly used types: microelectrodes - electrodes which are used to measure the potential either inside or very close to a single cell; needle electrodes - electrodes used to pass through the skin and record potentials from a small area, such as a motor unit within a muscle; and surface electrodes - electrodes applied to the surface of the body and used to record signals such as the ECG and EEG.

Microelectrodes are not used routinely in medical departments. They are electrodes with a tip small enough to penetrate a single cell and can only be applied to samples of neural tissue. A very fine wire can be used but the smallest electrodes consist of a tube of glass which has been drawn to give a tip size as small as 0.5µm; the tube is filled with an electrolyte such as KCl to which a silver wire makes contact. Microelectrodes must be handled with great care and special recording amplifiers used in order to allow for the very high impedance of tiny electrodes.

Needle electrodes come in many forms but one type is a concentric design used for electromyography. A fine platinum wire is passed down the centre of a hypodermic needle with a coating of epoxy resin used to insulate the wire from the needle. The needle is connected to a differential amplifier, to record the potential between the tip of the platinum wire and the shaft of the needle. The platinum wire tip may be as small as 200 µm in diameter. This electrode is used for routine needle electromyography as it allows the potentials from only a small group of motor units to be recorded.

Needle electrodes must be sterilised before use and they must also be kept clean if they are to work satisfactorily. Some electrodes are suitable for sterilisation by autoclaving but others must be sterilised in ethylene oxide gas. This form of sterilisation requires the needles to be placed in the ethylene oxide gas at 20 psi (140 kPa) for 1.5 hours at a temperature of 55-66°C. The articles must be left for 48 hours following sterilisation before use; this allows for spore tests to be completed and any absorbed gas to be cleared from the article.

Cleaning of the electrodes applies particularly to the metal tip where a film of dirt can change the electrical performance of the electrode; it is possible for dirt on the tip to give rise to rectification of radiofrequency interference, with the result that radio broadcasts can be recorded through the electromyograph!

The earliest types of surface electrode were simply buckets of saline into which the subject placed their arms or legs. A wire was placed in the bucket to make electrical contact with the recording system. There are now hundreds of different types of surface electrode, most
of which can give good recordings if correctly used. The most important factor in the use of any type of electrode is the prior preparation of the skin.

One of the problems with nearly all surface electrodes is that they are subject to movement artefacts; movement of the electrode disturbs the electrochemical equilibrium between the electrode and the skin and so causes a change in contact potential. Fig 2 shows how this problem can be overcome by moving the contact between metal and electrolyte away from the skin. A pool of electrolyte is placed between the silver chloride disc and the skin. Movement of the electrolyte does not disturb the junction between metal and electrolyte and so does not change the electrode potential.

There are very many other types of electrode. For example, conductive polymer electrodes can be used to make contact to the cornea and hence used to record electrical signals from the eye. These electrodes have to be flexible, non-toxic and sufficiently conductive to make contact to a wire and then to an amplifier.

![Diagram of electrode setup](image)

Or to be really simple, just this:

![Simplified diagram of electrode setup](image)

Fig 2 This floating electrode minimises movement artefact by removing the silver-silver chloride disc from the skin and using a pool of electrode jelly to make contact with the skin.

1.3 Bioelectric signals and amplifiers

Almost every part of the body produces electric signals. They are not just by-products but are essential control signals to make us function and, for that reason, electrophysiological measurements contain useful diagnostic information. All of these signals must be amplified before they can be recorded.
The electrical signals produced by the body are small. The largest is the ECG which has an amplitude of about 1 mV. This is much too small to drive any recorder directly or to input to a computer; hence, the signal has to be amplified. Amplification can be either of voltage or current. In general it is taken for granted that voltage amplification is required and that the amplifier will supply sufficient current to drive a recording device.

Obviously the amplifier gain required will be large if the signal to be amplified is small. An EEG amplifier will have a higher gain than an ECG amplifier because the EEG is only about 100 µV in amplitude. The gain of an amplifier is the ratio of the output and input voltages. In an ideal amplifier the gain is independent of frequency, but in a real amplifier this is not the case; thus, the frequency response of the amplifier has to be matched to the frequency content of the signal.

1.4 Frequency content of signals

Any signal has a certain frequency content. The French Scientist Baron de Fourier developed the concept of frequency analysis which is named after him. He showed that any repetitive signal can be considered as the summation of sine waves. If the fundamental frequency is \( f_0 \) then:

\[
f(t) = \sum_{n=0}^{n=\infty} a_n \sin(2\pi nf_0 t + \Phi n)
\]

where \( f(t) \) is the periodic signal, \( a_n \) is the amplitude and \( \Phi n \) the phase of the sine wave corresponding to a particular \( n \).

The ECG is a periodic signal whose lowest frequency component is the heart rate. If the heart rate is 60 per minute, i.e. 1Hz then the lowest frequency component is 1Hz. Fourier analysis shows that the complete ECG waveform can be produced by adding together sine waves of 1Hz, 2Hz, 3Hz etc. The amplitude of the components will determine the shape of the ECG.

![Fig 3](image)

The lowest frequency component of this ECG is at 1 Hz.

Frequency analysis of the ECG shows that the biggest component is at about 17 Hz and that the components above 100 Hz are of negligible amplitude. An ECG amplifier must be able to handle frequency components between 1 Hz and 100 Hz; it must amplify the components equally and preserve the relative phase of all the components.
1.4.1 **Bandwidth**

The bandwidth of an amplifier is the frequency range over which the gain remains constant. In practice, it is normally quoted as the -3 dB bandwidth; that is the frequency range over which the gain is not less than 3 dB below the maximum gain.

The bandwidth of an amplifier must be sufficient to handle all the frequency components in the signal of interest. Some common physiological signals and their approximate frequency contents are given in the table below:

<table>
<thead>
<tr>
<th>Signal</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>0.5 Hz - 100 Hz</td>
</tr>
<tr>
<td>EEG</td>
<td>0.5 Hz - 75 Hz</td>
</tr>
<tr>
<td>Arterial pressure wave</td>
<td>DC - 40 Hz</td>
</tr>
<tr>
<td>Body temperature</td>
<td>DC - 1 Hz</td>
</tr>
<tr>
<td>Respiration</td>
<td>DC - 10 Hz</td>
</tr>
<tr>
<td>Electromyograph</td>
<td>10 Hz - 5 kHz</td>
</tr>
<tr>
<td>Nerve action potentials</td>
<td>10 Hz - 10 kHz</td>
</tr>
<tr>
<td>Smooth muscle potentials</td>
<td>0.05 Hz - 10 Hz</td>
</tr>
</tbody>
</table>

Interfacing signals to computers must be done with great care. The computer will only handle digital signals so that the voltage must be sampled at regular intervals and the voltage at every point recorded. The rate of sampling must be high enough to handle all the frequency components of the signal.

1.5 **Noise and Electrical interference**

Noise is any unwanted signal. It may be hiss on a recording of music or snow on a TV picture. It can arise from the random motion of electrons in the recording system or from an interfering signal.

Electrical interference can be a problem when making almost any physiological measurement. Electrophysiological signals such as the ECG, the EEG and EMG are particularly susceptible to interference because they are small electrical signals. Laboratory instruments, nuclear medicine equipment, and even computing equipment can also be subject to interference from nearby electrical machinery such as lifts, air conditioning plant, and cleaning equipment.

1.6 **Differential Amplification**

Differential amplifiers are found in practically all systems for recording small physiological signals. Put simply, a differential amplifier will only pass signals that differ between its two inputs. Any signal that is the same at both inputs will be blocked. Thus, if the two inputs are connected to a patient via electrodes, any potential difference between them such as an ECG will be amplified, but any interfering signal picked up by the electrode leads such as mains interference will be blocked.
This diagram shows a low frequency signal from the patient that differs between the two inputs and is therefore amplified, with an interfering high frequency signal picked up by the leads that is the same for both inputs and is therefore blocked.

Note that the electrode leads must be kept together otherwise the interfering signals they pick up will differ and will not be blocked!