The recording of electrocardiograms, electromyograms and electroencephalograms requires the use of the highest gain amplifiers available in a recording system. Undoubtedly, the greatest nuisance in this type of work lies in the picking up of unwanted signals at the power line frequency (50 c.p.s. in the U.K., 60 c.p.s. in the U.S.A.). In the previous article in this series, the need was stressed to avoid at all costs the connection of the patient to the “line” lead of the mains power line, with the resulting possibility of a fatal electric shock. The unwanted “hum” signal is picked up by capacitative coupling between the input of the amplifier and the mains wiring in the operating room or laboratory. Associated with radio waves and power line currents there is both an electric and a magnetic field. Under clinical conditions, at power line frequencies, it is the capacitatively coupled electrostatic field which is picked up from the mains wiring. Electromagnetic pick-up could be appreciable if one was working close to a large power transformer. The pick-up action is shown in figure 1. A capacity \( C_1 \) exists between the input grid of the amplifier and the mains wiring. A capacity \( C_2 \) exists between the input valve cathode of the amplifier and earth. The case of the amplifier is coupled by capacitances \( C_3 \) and \( C_4 \) to the mains wiring and to earth. The amplifier is of the “single-sided or unbalanced” type and the two resistors “R” represent the electrode skin resistances. It can be seen that the four capacitances form an AC Wheatstone bridge network. If this is not balanced, the output voltage of the bridge appears across the resistances “R”, and hence between the grid and cathode of the input valve, and constitutes an unwanted signal which is amplified. A significant interference occurs even though \( C_1 \) may have a value of only a few picofarads. Earthing the amplifier chassis would not help, but would in fact make the interference much worse. Then \( C_1 \) would be short-circuited and the bridge completely unbalanced. It is possible to eliminate this mains interference by placing the patient inside a cage made of wire mesh, and using a battery powered amplifier. It is not always practical to work in a screened room or cage. However, a screened enclosure can be of great use in eliminating strong interference from therapeutic diathermy equipment, or interference from television stations. The design of screened enclosures is discussed by Leadbitter (1963).

Because it is not normally practical to work without the presence of an electrostatic field from the mains, it is customary to use balanced amplifiers for biological recording. By means of cathode degeneration techniques, the amplifier is made to discriminate against the unwanted signal which will be in-phase at the two input terminals. The use of a balanced amplifier is shown in figure 2. The case of the amplifier is earthed, and the patient is connected to earth by an extra electrode which has a skin resistance of \( R_3 \). The skin resistances of the input electrodes are \( R_1 \) and \( R_2 \). It is seen that the patient is connected across the AC power line by a potentiometer network consisting of the impedance \( Z_1 \) of \( C_1 \) and resistance \( R_3 \). Thus the
patient will develop a voltage with respect to earth equal to the mains voltage multiplied by \( R_3/(Z_f + R_3) \). This voltage, divided by the discrimination factor of the amplifier will represent the unwanted input signal. The discrimination factor is defined as the ratio of the amplifier gain for out-of-phase signals to the gain for in-phase signals. For a good amplifier alone this may have a value of 10,000. However, the discrimination factor of the recording system as a whole, will depend on the values of the electrode skin resistances \( R_1 \) and \( R_2 \) and the input capacitances \( C_2 \) and \( C_3 \). This point is further developed in figure 3.

ELECTRODE represents tissue and blood resistances, and are negligibly small compared with the other resistances. If the amplifier were perfectly balanced, that is, had an infinite discrimination factor, then equal in-phase voltages \( V_a \) and \( V_b \) would give rise to a zero output. However, the actual voltages \( V_a \), \( V_b \) depend on the values of \( R_1 \) and \( R_2 \). Any difference between \( V_a \) and \( V_b \) will be amplified by the amplifier, even though the signals are in-phase. It can be shown that an electrostatic interference signal \( V_E \) will produce the same amplifier output as a wanted signal from the patient of magnitude

\[
\frac{(R_2 - R_1) V_H}{R_{IN}} \frac{1}{2}
\]

Thus the discrimination factor between wanted and unwanted signals is

\[
\frac{R_{IN}}{2} \frac{1}{(R_2 - R_1)}
\]

If the total input resistance was 2 megohms, and the electrode skin resistances were 5 k-ohms and 3 k-ohms, the discrimination factor would be 500. It is seen that the amplifier input resistance should be high, and the electrode skin resistances should be low, and as nearly equal as possible. With a good technique of abrading the horny layer of the skin, and applying electrode jelly, electrode skin resistances of the order of 3 to 5 k-ohms can be obtained. It is a good idea to use a simple “ohm-meter” type of resistance tester to check the electrode skin resistances before the start of recording. In extreme cases of interference, an additional resistance can be used, as shown in figure 4, to equalize the effective electrode resistances.

Earth loops.

In the construction of high-gain amplifiers, it is usual to connect all the points in the circuit which have to be earthed to an insulated busbar which is connected to a good earth. Thus there is only one principal connection to earth, and currents cannot flow through the amplifier chassis or cable screens since these are only connected once to the busbar. The action of a shielded cable is illustrated in figure 5. The input cable to the amplifier is surrounded with a woven wire mesh
which is earthed. Electrostatic coupling exists between the room mains wiring and the mesh, but no field can exist inside the mesh. The action of an earth loop is shown in figure 6. Suppose that the input cable screen and one end of the amplifier input resistance were connected to different points on the amplifier chassis, then the chassis completes a loop circuit which can pick up electrostatic interference from the mains. Adjacent to the patient there should be several earth terminals in parallel. These should be connected by a copper strip to a copper plate, or a series of copper rods, buried in damp ground. The central earth connection of each piece of recording equipment should be connected to one of the terminals of the earth system for the room. As described in Part V of this series, the earth cores of the mains leads to each piece of equipment should not be connected to the earth system for the room.

The usual AC mains supply consists of three connections, line, neutral and earth. There is normally only a volt or two difference between the neutral and earth. From such wiring there will arise a strong electric field as the line lead fluctuates from the positive to the negative peak values of the mains voltage. This unwanted electrostatic field can be greatly reduced by supplying the mains power to the recording room or operating theatre from a balanced centre-tapped mains transformer as shown in figure 7. The voltages appearing at either end of the centre-tapped secondary winding are equal in magnitude, but in antiphase. As a result, the electrostatic fields from each wire cancel. At the University of Nijmegen in Holland, the use of such transformers has been found to reduce the mains field in recording rooms by some fifty times. It should also be remembered that radio frequency currents from surgical and therapeutic diathermies can be passed back to recording rooms along the mains wiring. Radio frequency filter networks should be fitted to the mains supply at the entrance to recording rooms. Magnetic field interference is best dealt with by moving the

**Fig. 4**
The use of balancing resistors to make up for unequal electrode skin resistances.

**Fig. 5**
The shielding effect of a screened cable.

**Fig. 6**
The action of a "Ground Loop".

**Fig. 7**
The use of a balanced mains transformer.
recording equipment as far away as possible from the source of the field. Inductances in an electronic circuit are particularly prone to have induced in them a voltage from varying stray magnetic fields. In this case the inductor should be surrounded by a case of soft magnetic material, such as Mumetal.

**TRANSDUCERS**

The Fifth International Conference on Medical Electronics was held in July 1963, at Liège, Belgium. For this conference, which was on the theme of transducers, the following definition was made. “A physical transducer for medical application is the first link in the chain which transmits information from a living system to a measuring system.” Some quantities connected with a living system are in an electrical form already. These usually require amplification, and can be caused to actuate a suitable recorder. Obvious examples occur in the case of action potentials, the electrocardiogram and the electroencephalogram. Other quantities such as blood oxygen tension, or alveolar carbon dioxide tension require transforming (transducing) to a corresponding electrical signal. The types of transducer which come under this general heading are extensive and include pH meters, infra-red gas analyzers, oxygen polarographs, carbon dioxide electrodes and blood flow meters. Each of these topics has its own specialized literature, and space considerations prevent them from being discussed in detail in this series. A decision is made to concentrate on pressure transducers.

**Pressure Transducers**

Pressure is defined as force per unit area. Accordingly, if the pressure to be measured is applied to an area, in the form of a flexible diaphragm, then the diaphragm will be deformed by the pressure. Electrical means are used to measure the motion of the diaphragm. It is desirable that the motion should be linearly related to the pressure. The basic operating principle is the conversion of a small change in the geometry of the transducer into a large change in some electrical quantity. The three main types of pressure transducer are the capacitance manometer, the differential transformer and the strain gauge. Other subsidiary types will be mentioned.

The strain gauge.

In engineering, one is often concerned with the application of tensile or compressive forces to beams and the resultant change in length of the beam. The force per unit area is known as the stress, and the increase in length per unit length is known as the strain. Strain gauges were developed as a means of measuring the small changes in length. Their basic operating principle lies in the fact that if a wire is stretched, its electrical resistance is increased. Conversely, if it is contracted, the resistance is decreased. Changes in resistance will arise from an increase in length of the wire, a decrease in its cross-section, and a small change in the resistive properties of the wire material. The “Gauge Factor” of a strain gauge is defined as

$$F = \frac{r}{R} \times \frac{L}{L}$$

where $R$ is the original resistance of the strain gauge, $r$ is the change in resistance, $L$ is the original length of the wire, and $l$ the change in length. A Nichrome wire strain gauge of resistance 200 ohms has a gauge factor of 2.25, and a stainless steel gauge of 200 ohms has a factor of 3.1. The gauge factor of the wire mainly determines the sensitivity of the gauge. The wire should also be chosen to have a low temperature coefficient of resistance. In a practical strain gauge, the wire is formed into a zigzag pattern and is firmly bonded on to an impregnated paper. The dimensions of the 200 ohm Nichrome wire gauge are 25 mm long by 4 mm wide. In use the gauge is firmly glued or bonded on to the member whose movement is to be recorded. Hence this type is known as a “Bonded Strain Gauge”.

Consider a cantilever as shown in figure 8, with one gauge bonded to the upper surface and a second gauge bonded to the lower. Let the two
STRAIN GAUGES
HALF BRIDGE

STRAIN GAUGES
FULL BRIDGE

FIG. 9A
Half and full strain gauge bridges.

FIG. 9B

The variable capacitance transducer.

Capacitance manometers work on the principle that the electrical capacitance existing between a pair of metal plates alters with the spacing apart of the plates. The closer the plates, the greater the capacitance between them. One plate is normally fixed, and the other is the diaphragm to which the pressure is applied. The separation of the plates can be made very small, so that small movements of the diaphragm give rise to a substantial change in capacity. Capacitance manometers are used where a high sensitivity and natural frequency are required. However, their temperature stability is not so good as that for strain gauge and inductance types, and hence at present these types are more popular. The capacitance of the gauge is used as part of the tuning element of the oscillator in a frequency modulation system, or as a reactive element in an audio frequency AC bridge. If the capacitance manometer is connected by a flexible cable, the capacitance of the cable will also form part of the tuning circuit. The capacity of the cable in parallel will tend to reduce the sensitivity of the arrangement. The temperature sensitivity of the cable capacitance may give rise to a significant base line shift. Haines (1960) has described a useful circuit which has been used with lengths of cable up to 300 feet. The classical articles on the use of capacitance manometers are those of Lilly et al. (1947) and Hansen (1949). Capacitance manometers are frequently used in conjunction with a "Pneumotachograph Head" to measure gas flow patterns in breathing circuits (Lilly, 1950; Hill, 1959). The electrical signal from the pneumotachograph pressure transducer gives the time variation of the volume flow rate (litres per minute). This can be fed into an electrical integrating circuit, to yield the tidal and minute volume.
The variable inductance transducer.

The effective inductance of a coil can be altered by changing the position of a core of magnetic material lying within the magnetic field of the coil. The coil is made to form part of an audio frequency AC bridge, or to act as the tuning inductance of a telemetry transmitter, as in a "radio pill" (Jacobson, 1950). The diaphragm affected by the pressure is attached to the core. Only a small core movement is permissible in order to obtain a linear change in inductance with core position. A more commonly encountered inductance transducer is the "Differential Transformer" shown in figure 11. With the core symmetrically placed between the primary and two secondary windings, the voltages induced in each of the secondaries is equal, but opposite in phase.

![Diagram of the differential transformer transducer.](https://example.com/diagram.png)

Thus, under these conditions, there will be zero output voltage from the series-connected secondaries. When pressure is applied to the diaphragm, the core is moved, and the voltage induced in one of the secondary windings exceeds that induced in the other. As a result, there will now be a net output voltage. Sanborn pressure transducers work on this principle.

Amplifier systems for use with transducers.

Figure 12 illustrates the various circuit arrangements used with transducers. In arrangement No. 1 a simple DC bridge is used, the output from the bridge being fed to a DC amplifier. Here, care must be taken to watch for changes in the bridge supply voltage and drift in the DC amplifier. In arrangement No. 2 the bridge is used indirectly. The bridge output voltage modulates the amplitude of an audio frequency carrier signal. The output of the carrier is fed into a phase-sensitive rectifier, so that the sign of the output voltage is positive if the pressure to be measured is positive, and negative if the pressure is negative. Although the carrier system is more complex, the direct-coupled DC amplifier has been eliminated. These two DC bridge arrangements would only be suitable for use with a resistive transducer such as a strain gauge.

Inductance and capacitance transducers which are of a reactive nature can be used in an AC bridge as shown in arrangement No. 3. This will also handle resistive strain gauges. This scheme is used in some of the well-known Sanborn recording systems. Alternatively, as in arrangement No. 4, the reactive element can be used to effect the oscillation frequency in a frequency-modulation system. This system is used in the Respiratory Analyser by Vickers Research Limited. Finally, as in arrangement No. 5, a frequency modulation telemetry system may be used.

General considerations in the use of pressure transducers.

In order to obtain a faithful reproduction of a blood pressure contour or a pneumotachogram, it is important to consider the hydraulic or pneumatic system as a whole. As a working rule, it is taken that a faithful reproduction of a waveform can be recorded by a system which has a uniform frequency response at least up to the tenth harmonic of the fundamental frequency of the signal. With a 2 cycles per second pulse (120 beats per minute), the recording system must have a level frequency response up to at least 20 c.p.s. Care must be taken to obtain a good frequency response when a long cardiac catheter is connected to the transducer. The range of frequencies over which the amplitude response of the system is uniform depends on the "undamped natural frequency" of the system and the damping. Crul (1962) described an elegant method of "parallel" damping, and recommends the use of a small bore (No. 4 or 5) stiff catheter in conjunction with a transducer having a small volume pressure chamber with a stiff diaphragm. The volume change in the transducer should be of the order 0.01-0.05 c.mm/100 mm Hg. Crul also describes a neat hydraulic...
压力传感器用于检查血压记录系统的频率响应。他建议压力室部分应能够与电子部分分开。在这种方式下，有可能将压力室中的空气泡完全排出，这会破坏频率响应。与长液柱在导管中的相关问题可通过在导管尖端安装一个小型压力传感器来解决。一个良好的一般性介绍和许多其他传感器由Shirer (1962) 给出。对于呼吸计，McCall et al. (1957) 表明至少需要30 c.p.s.的频率响应。

REFERENCES