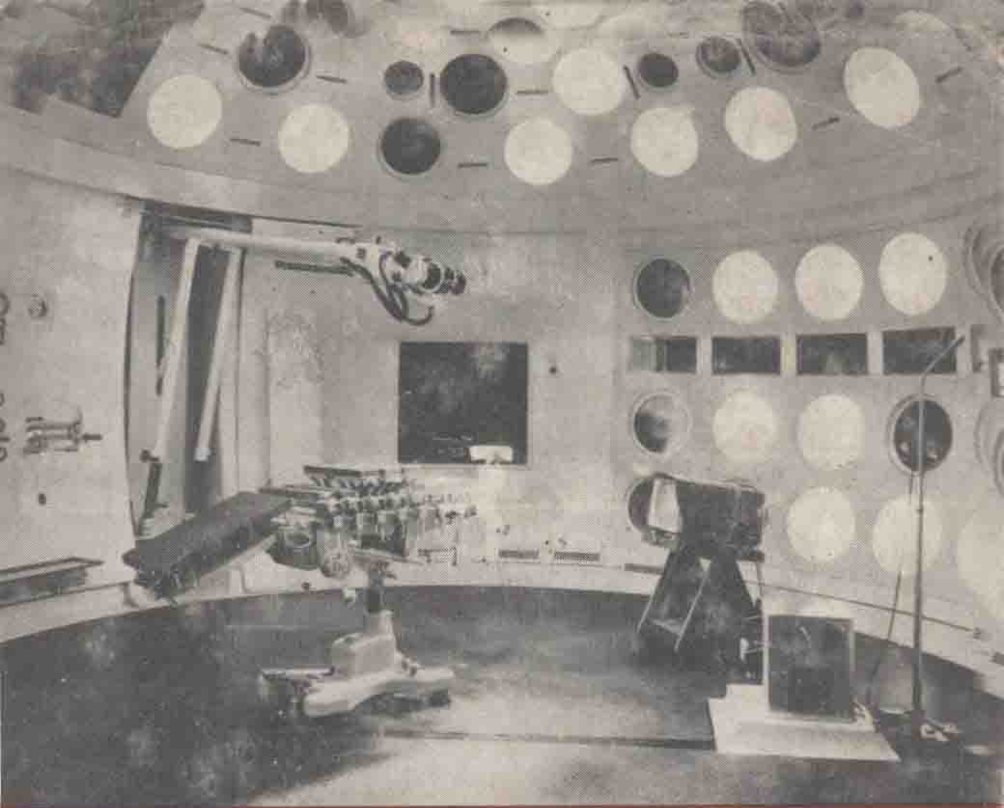

Principles of Electronics in Medical Research

D. W. Hill

Butterworths

PRINCIPLES OF
ELECTRONICS
IN
MEDICAL RESEARCH

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PREFACE

The contents of this book are based on the series, 'Some Fundamentals of Medical Electronics', which appeared in the *British Journal of Anaesthesia*, and experience gained over several years of teaching scientists and doctors on the 'Laboratory Course in Medical Electronics', held at the Royal College of Surgeons of England.

Increasing instrumentation is being used in medical and biological laboratories, but many of the staff lack a basic grounding in the fundamentals of electronic engineering. When doctors are responsible for electronics staff, and for ordering equipment and spares, it is desirable that they have some knowledge of what is involved, and what the various technical terms mean, if only in outline. This applies also to technicians responsible for operating equipment in medical departments, in order to obtain the most effective functioning of the apparatus.

The basic devices and circuits are dealt with in a descriptive fashion, since a knowledge of detailed design is best left to the electronic engineer. In a single volume, it is not possible to give details of all the applications of electronic techniques in medicine. Wherever possible, references have been given for further reading, so that workers in a particular specialty can find information on techniques which will be of use to them. Counting techniques for use with radioisotopes have been deliberately excluded, since these are well covered elsewhere.

It is a pleasure to acknowledge the encouragement of the editorial staff of the *British Journal of Anaesthesia*, and of my colleagues on the staff, and many students, at the Royal College of Surgeons. Without their patient co-operation, I would not have been able to gain an appreciation of the power of modern instrumental techniques in medical research.

D.W.H.

CONTENTS

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MAGNETISM AND ELECTROMAGNETISM

PERMANENT MAGNETS

The fact that an iron needle, when rubbed with lodestone and freely suspended, acts as a compass and aligns itself in a North–South direction has been known from early times. A piece of lodestone (leading stone) can also be used as a compass, hence the name. Needham (1962) mentions a Chinese text describing the use of a magnetic needle compass as early as A.D. 1080, about a century before its first European use. The magnetic attraction of lodestone to iron was mentioned in the late 3rd century B.C. An interesting connection with medicine is provided by William Gilbert (1546–1603), Personal Physician to Queen Elizabeth I, who published his work 'On the Magnet and on Magnetic Bodies, and concerning that great magnet the Earth, a new physiology'.

The availability of compact, powerful permanent magnets has made possible the construction of biological recording equipment of various types. These are described in Chapter 14. Whether the method of writing is ink on paper, heated stylus, ink jet or photographic, a powerful magnet is needed. It is interesting to note that in order to obtain a high degree of sensitivity for his experiments on animal electricity, Emil Du Bois Reymond had to wind 3·17 miles of wire on his galvanometer coils (Bence Jones, 1852). This was before the availability of powerful magnets.

Permanent magnets are found in moving-coil galvanometers, moving-coil meters, loudspeakers, magnetic stirrers and in paramagnetic oxygen analysers.

The Magnetic Field

In the space surrounding every magnet there exists what is called a magnetic field. If a strip of magnetic material, a bar magnet, is dipped in iron filings, then the filings will be attracted to each end of the magnet. These preferred regions of attraction are called Magnetic Poles. If the magnet is freely suspended, it will take up a North–South position. The end pointing towards North is called the 'N' or north-seeking pole. The other end is the 'S' or south-seeking pole. Like magnetic poles will repel, and unlike poles attract each other.

Two similar poles of unit strength placed one centimetre apart in a vacuum will repel each other with a force of one dyne.

If a small compass is placed at some point near the N pole of a straight bar magnet and then moved always in the direction that the compass is pointing, the centre of the compass needle will trace out a smooth magnetic line of force. By starting at different points, many such lines may be plotted as shown in *Figure 1.1*.

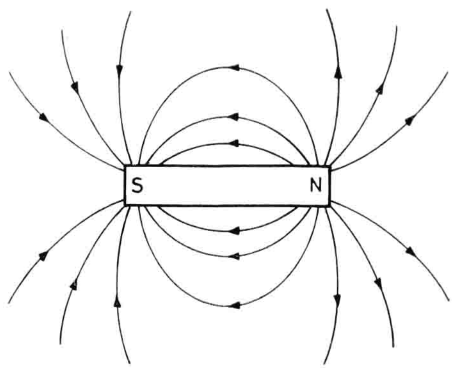

Figure 1.1. Magnetic field due to a bar magnet

These magnetic lines of force do not really exist. They are simply useful devices for describing magnetic phenomena. Where the magnet exerts its strongest attraction close to the poles, the field is greater, and the lines are closest together.

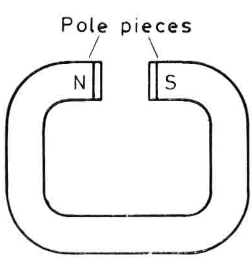

Figure 1.2. Galvanometer magnet

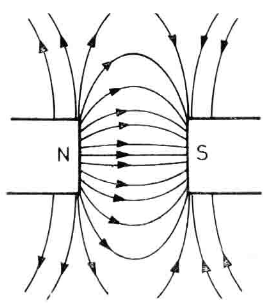

Figure 1.3. Field in the gap of a galvanometer magnet

The magnets used in rapid response pen recorders are shaped as in *Figure 1.2.* The magnetic field is concentrated in the gap between the pole pieces (*Figure 1.3*). The cylindrical iron core is omitted in this diagram. The strength of a magnetic field is numerically equal to the force in dynes acting on a unit pole placed at the point considered. The unit is the oersted. In a field of 5,000 oersteds, a force of 5,000 dynes would act on a unit pole. The strength of pen recorder magnets would be of the order of several thousand oersteds.

It is not often that the magnets have to be removed from the magnet block, but when this happens they should be treated with respect. Dropping them can reduce their strength. The use of a steel 'keeper' bar placed across the pole pieces will prevent self-demagnetization, which occurs when the magnets are stored.

TYPES OF MAGNETISM

Ferromagnetism

The commonly encountered permanent magnets are of the ferromagnetic type. They are composed of myriads of tiny elementary magnets. Before a piece of iron or steel has been magnetized, these elementary magnets may be thought of as being orientated virtually at random. During the process of magnetizing the iron, the elementary magnets are made to align with the magnetizing field.

Paramagnetism

Some substances, notably oxygen in medical applications, exhibit a form of magnetism which is weak compared with ferromagnetism Bates (1961). This property is utilized in paramagnetic oxygen analysers.

THE BEHAVIOUR OF MAGNETIC SHIELDING

The effect of placing a piece of soft iron in a uniform magnetic field is shown in *Figure 1.4*. The soft iron is seen to have the effect of concentrating the magnetic lines of force so that they pass through the soft iron in preference to passing through the air. An alloy such as

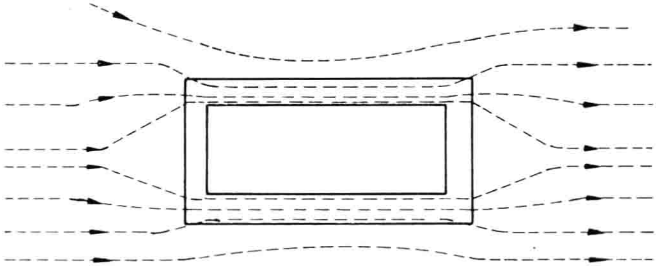

Figure 1.4. The action of a piece of soft iron on a magnetic field

mu-metal is considerably more effective than iron. Hence, it is usual practice to place circuits which must be shielded from stray magnetic fields inside a mu-metal box, the action of which is to 'screen' the circuit from the field. The electron beam in a cathode ray tube is susceptible to influence from stray magnetic fields; for this reason the cathode ray tube in an oscilloscope is usually mounted inside a mu-metal shield.

ELECTROMAGNETISM

The first discovery of any connection between electricity and magnetism was made by Hans Oersted in 1820. Oersted was born the son of an apothecary, graduated in medicine in Copenhagen, and subsequently became Professor of Physics at Copenhagen. He placed a current-carrying wire parallel to a magnetic compass needle, and found that the needle was deflected. Soon after, Ampère found that a loop or coil of wire acted as a magnet when an electric current was passed through it. The available magnetic field is greatly increased if the coil is wound on a soft iron core (*Figure 1.5*).

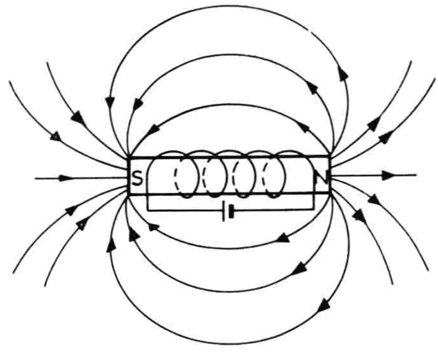

Figure 1.5. Field due to a simple electromagnet

Electromagnets are commonly encountered in the form of 'solenoids', used to produce mechanical movement. The magnetic field arising when current is switched through the coil attracts an iron armature which is free to move, and is attached to the object to be moved. Solenoid-operated valves are of great use in gas sampling systems. Hill and Stone (1963) describe a solenoid-operated gas sampling pump which can be used to sample potentially explosive anaesthetic mixtures.

Another very common application of electromagnetism occurs in electromagnetic relays. The relay coil is wound on an iron core. The pull of the electromagnet attracts a pivoted soft iron armature. The movement of the armature is caused to open or close pairs of electrical contacts, as required. For general purpose applications, Post Office type relays (Atkinson, 1947) are used. Special high speed relays, capable of being driven at mains frequency, are used in 'chopper' type d.c. amplifiers. A concise account of relays for use in biological applications is given by Machin (1958).

The closure or release of the relay contacts can be delayed by the mounting of the appropriate copper bands or 'slugs' on the iron core of the relay coil. Consider the case of a slow release relay. When the coil current is switched off, the collapsing magnetic field induces an eddy current in the low resistance slug. This gives rise to a temporary field which holds on the relay armature for a period of perhaps 100 msec before it releases. For normal relays releasing times would be of the order of 30 to 40 msec. Slow release relays were used by Hill and Hook (1958) to switch the solenoids of a solenoid-operated inspiratory–expiratory valve. The slow release action ensures that when switching occurs, the valve that is shut stays shut until the other valve closes, whereupon the first valve opens. At no instant are both valves moving, as would occur with a simple change-over action. Thus gas leakage past the valves is prevented.

Solenoids are available for operating from mains frequency a.c. supplies. Copper 'shading' rings fitted to the core produce a reasonably steady pull with a.c. energization. A.C. solenoids are useful when considerable power is required, but the unsteadiness (chatter) of the pull can be troublesome in some applications.

TRANSFORMERS

When a coil carries a changing or alternating current, in contrast to a steady or direct current, a changing magnetic field results. Consider two separate coils, wound one on top of the other. When a varying current flows in one coil (called the primary coil), a varying magnetic field is produced. The lines of force will intersect the second (secondary) coil. When a coil is cut by a changing number of magnetic lines of force, a voltage is induced in it. The magnitude of the voltage depends on both the number of lines cutting the coil, and the number of turns in the coil. Thus if both coils have the same number of turns, the voltage induced in the secondary coil will equal that in the primary, assuming the number of lines cutting the two coils is the same. When the secondary has twice as many turns as the primary, the secondary voltage will be twice the primary voltage. Such a device is known as a transformer. A transformer can be thus used to raise or lower an alternating (a.c.) voltage, but not a direct (d.c.) voltage. Mains transformers are encountered in the large majority of electronic apparatus. The mains supply voltage is applied to the primary winding. Secondary windings provide the various voltages needed for the operation of the electronic circuits.

The transformer does not contain any active elements capable of producing electrical power. Neglecting any losses, the power in the primary should equal the power in the secondary(s). Using the appropriate r.m.s. values (Chapter 5), the electrical power is given by the product (voltage × current), in the circuit concerned. Neglecting power losses

$$\text{Primary voltage } (V_p) \times \text{primary current } (I_p)$$
$$= \text{Secondary voltage } (V_s) \times \text{secondary current } (I_s)$$
$$V_p I_p = V_s I_s$$

If the secondary voltage is one-fifth of the primary current, the secondary current will be five times as large as the primary current. Ohm's law (Chapter 4) defines the resistance of a circuit (the opposition offered by the circuit to current flow) as having a value R in ohms given by $R = V/I$.

Consider a transformer having a 5 : 1 step-down ratio. Suppose that when 50 V r.m.s. is applied to the primary, a current of 1 A r.m.s. flows in the primary. The secondary voltage will be 10 V, and the secondary current 5 A. The effective resistance of the primary is $50/1 = 50$ ohms. That of the secondary is $10/5 = 2$ ohms. The ratio of primary to secondary resistance is $50/2 = 25 : 1 = 5^2 : 1$. The effective resistance in the secondary is related to that in the primary, by the square of the turns ratio. Transformers are often used to change the effective resistance of a circuit. Thus a 'matching transformer' is used to match the high resistance circuit of the output valve of an audio amplifier into the low resistance of a loudspeaker coil. Matching transformers were much used to obtain the best power transfer between stages in transistor a.c. amplifiers. However, transformers are not looked upon with favour in modern circuitry. They tend to be microphonic, and are prone to the effect of unwanted stray magnetic fields. Since the price of transistors has fallen markedly, it is preferable to use more transistors to attain the desired degree of amplification, and to eliminate the transformers (Cherry, 1963).

At power-line frequencies, transformer coils are wound on a laminated steel core. The thin sheet laminations reduce eddy currents induced in the core, which would waste power. At audio frequencies, small laminated cores of special alloys are used. At radio frequencies, the coils do not have a solid core, being 'air-cored', just wound on a hollow former. They may, however, have a ferrite core. The core is fabricated from a large number of small particles of ferrite material, compressed and held together with a binder material. Ferrite cored transformers are used in the tuned circuits of very high frequency (v.h.f.) telemetry systems.

EDDY CURRENTS

When a changing current is flowing in a conductor adjacent to a piece of metal, the changing magnetic field induces 'eddy' currents in the metal. The term eddy current arises from the fact that the

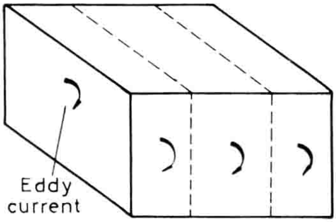

Figure 1.6. Eddy currents circulating in a solid core

induced current whirls around the metal like eddies in water. If an alternating current flows in a coil wound on a solid iron core, eddy currents flow in the core (*Figure 1.6*), which becomes warm if the power involved is sufficient. This heating represents a waste of the electrical power supplied to the transformer. To reduce eddy currents, audio and mains frequency transformer coils are wound on

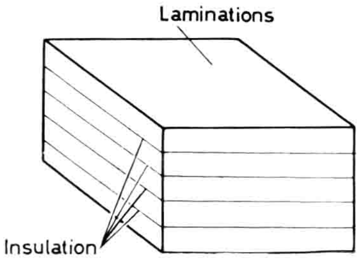

Figure 1.7. A laminated core

cores constructed from a series of thin sheets (laminations) of special iron or alloy material (*Figure 1.7*). The laminations are insulated from each other, so that the currents can now no longer circulate in the bulk of the metal.

Applications of Eddy Currents to Therapeutic Diathermy

In transformer design, attention is paid to the reduction of eddy currents. However, the heating of tissue by induced eddy currents is the basis of treatment by therapeutic diathermy units operating at 27 Mc/s.

PROPERTIES OF MAGNETIC MATERIALS

For many years, it was known that soft iron could be magnetized and demagnetized easily, and was therefore suitable for use as the core material of an electromagnet. On the other hand, steel could only be magnetized and demagnetized with difficulty, and could thus be made into a permanent magnet.

Intensity of Magnetization (J)

The Magnetic Moment (M) of a magnet is given by

$$M = \text{Pole strength} \times \text{Magnetic length}$$

where the magnetic length is the distance separating the poles. The length would be measured in centimetres, and the pole strength in c.g.s. (centimetre-gram-second) units. The Intensity of Magnetization (J) of the material is defined as the magnetic moment per unit volume. If the cross-sectional area of the magnet is constant, the intensity of magnetization is equal to the 'pole' strength per unit area.

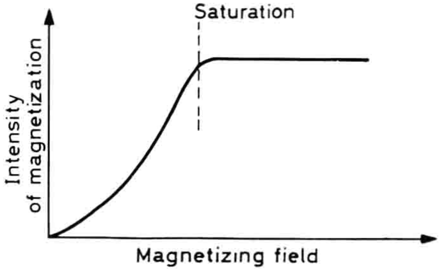

Figure 1.8. The onset of saturation when the magnetic field is too high

When a magnetic material is magnetized by placing it in an increasing magnetic field, it is found that the intensity of magnetization increases to a maximum when the material becomes saturated (*Figure 1.8*).