PRACTICAL APPLICATIONS OF ELECTRONICS IN ANAESTHESIA

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PART I: BASIC PRINCIPLES

In the last twenty years much has been heard of the art of electronics and its applications in science and technology. Parallel with these developments electronics has had a rapidly increasing field of application in clinical medicine and surgery, and its scope appears at the moment to be almost unlimited.

It is the purpose of this article first to explain briefly the basic principles of electronics and how they are applied, and then to discuss some applications to clinical work which may be of special interest to the anaesthetist. It is hoped that any reader whose acquaintance with the subject is limited may thus be enabled to visualize how electronics could be of further assistance in his own work.

All electronic devices depend for their operation on the fundamental laws of electricity. While the adjective "electronic" has the literal meaning "pertaining to electrons", the word, together with its associated noun "electronics", has a more limited meaning in everyday usage. As is well known, a current of electricity flowing in a metallic conductor consists of a drift of "free" electrons (i.e. electrons which are not firmly bound in atomic orbits) under the influence of a single potential difference (or pressure) applied between the ends of the conductor. The relation between the potential difference and the current is embodied in Ohm's law.

In the thermionic valve, however, the electrons are made to exist in a condition where their motion is much more susceptible to outside influences such as electric fields, other potential differences or currents, etc. This is done by causing the electrons to form a cloud in free space, where they can be attracted or repelled by charged electrodes in the valve. In the transistor, a more recent development, the electrons exist within the crystal lattice of a semi-conductor and there they may readily be influenced by other currents.

In this way a large current (of electrons) may be controlled by a small voltage or current, and thus the primary function of thermionic valves and transistors is that of amplification. For example, the small electrical action potentials accompanying the normal functions of nerves and muscles can be amplified to a level at which they are capable of operating recording apparatus as described later. Associated with these basic electronic devices is usually found a number of ordinary electrical circuits and components such as resistances and inductances, which are necessary for the correct functioning of the amplifier.

Electronic amplifying circuits, however, will perform other functions. For example, if the nature of the amplification is non-linear, the mode of variation, known as the waveform, of the output voltage or current will differ from that of the input. The circuit is then said to "shape" the waveform, and we are unpleasantly aware of this phenomenon when, because of some accidental non-linearity, the output of our domestic radio receiver becomes distorted and unlike the original sound. Alternatively, by causing part of the output voltage of an amplifier to be fed back to the input in a suitable manner the circuit will produce voltages or currents of any desired waveform. These functions will be explained in greater detail later.

So far we have considered the amplification, shaping and production of purely electrical quantities by means of electronic devices. By the incorporation of another sort of component, called
a transducer, the scope of an electronic system may be greatly increased. A transducer is a device which will convert electrical energy to other forms of energy or vice versa. Familiar examples are the microphone, which converts sound into electrical energy, and the electric motor, which produces mechanical from electrical energy. Thus, for example, if we precede an electronic amplifier by a transducer designed to convert pressure into voltage changes, the system will become a very sensitive pressure gauge. Moreover, if the amplified electrical output is then fed into another transducer which will write on a moving strip of paper or photographic film, the pressure changes may be recorded in as permanent a form as desired. Alternatively, the output transducer may be designed to control some function which must depend upon the value of the input pressure. For example, the blood pressure in an artery or vein may be used to control the action of a mechanical pump which is artificially maintaining the flow of blood during surgery. These facilities, of course, depend entirely on the amplification which is obtained from electronic devices and their associated circuits.

The main functions of electronic systems are therefore:

1. the amplification, shaping, and production of voltage and current waveforms;
2. the recording or storage of the amplified voltages;
3. the use of such voltage waveform for control purposes.

In fact there is a very close parallel between electronic apparatus and the nervous system. For example, the sensory organ of the eye acts as a transducer which converts light into electrical energy: this is, in a sense, amplified and shaped by fibres in the optic nerve and finally conveyed to the brain. Here the brain acts also as a transducer, not only presenting the information in a form intelligible to the organism but often also recording the information as an act of memory. Again, waveforms may be produced in the brain and conveyed via a motor nerve to the muscle which acts as a transducer producing mechanical energy. It is unwise, of course, to press the analogy too far, but it has been further found that when two or more systems interact, for example a sensory and a motor link, the dynamics of the electronic and of the living systems are very similar.

Two important properties of electronic systems have not yet been mentioned. In electronic measuring instruments, because of the high degree of amplification available, it can be arranged that the apparatus absorbs negligible power (electrical or otherwise) from the source of the effect being measured. It therefore introduces little disturbance and we may be tolerably sure that the magnitude of the effect observed will be similar in the absence of the measuring apparatus. Moreover, due to the small inertia of the electron the speed of the electronic system is for present purposes limited only by any mechanical components, i.e. transducers, in the system. In practice, it is easy to design apparatus which will follow the fastest changes encountered in biological systems, but for other reasons, as will be explained later, the design of some types of transducer may be difficult.

**Thermionic valves.**

Although the transistor is being rapidly developed as an alternative to the thermionic valve in some applications, the latter still remains by far the most important electronic device, and it will therefore be treated in some detail.

The operation of the valve depends upon the phenomenon of thermionic emission. At normal temperatures the free electrons in a conductor have insufficient energy to leave the surface of the conductor. If, however, the metal is heated to an appropriate temperature, ranging from dull red to white heat, in an evacuated vessel, the free electrons will be energetic enough to escape into the surrounding space where they form a negative "space charge". All thermionic valves contain such a conductor, called the cathode, which may be in the form of a heated filament or cylinder of metal.

The diode, as its name implies, contains two electrodes, the emitting cathode and a plate called the anode. This valve has a very important property. If the anode is maintained at a potential positive with respect to the cathode by a battery connected between the two electrodes, the electrons emitted by the cathode will move across...
the interelectrode space and strike the anode. These electrons will flow round the external circuit and form the "anode current". If, however, the anode is negative with respect to the cathode, the electrons will be repelled and no current will flow. Thus the diode acts as an automatic one-way device for electric currents, its operation being determined by the difference of potential between its two electrodes. In this respect its action is very similar to that of a one-way valve for liquids, which opens and shuts according to the pressure difference across it.

The uses of the diode are somewhat limited, but the valve is important in two ways. First, because of its one-way action it may be used to convert alternating current into direct. This process is called rectification, and the diode forms the basis of all power supply units, which may be separate or part of other electronic apparatus, and which operate from the alternating current mains and supply direct current for other valves, etc. Second, it is important as the basis of the triode, a device which will perform most of the functions called for in electronic apparatus.

The triode is similar to the diode in construction, but the electron stream in its travel from cathode to anode passes through a third electrode called the grid. This is usually in the form of a helix of fine wire, so that geometrically it allows free passage to the electrons. The flow of electrons, and hence the anode current, however, may be controlled by varying the potential of the grid relative to the cathode. Figure 1 shows a triode connected in a simple circuit to demonstrate its properties, and figure 2 is a graph relating anode current (Ia) to grid voltage (Vg). If the grid is at cathode potential, its presence has little effect on the anode current. If, however, the grid is made negative, electrons are repelled back to the cathode space charge and the anode current decreases, reaching a value of zero at the "cut-off point". Application of a positive potential to the grid results in increased anode current, because the force of attraction exerted by the grid is added to that of the anode. In this way the anode current, which may be quite large, may be made to vary in sympathy with changes in the grid potential. The triode is therefore the electrical analogue of a non-automatic valve or tap, in which the flow of liquid is controlled by some external influence.

To appreciate fully the value of the triode as an amplifier we must consider further the power expended in grid and anode circuits. In the latter an appreciable current flows at a high potential difference, and hence the output power available is large. In the condition when the grid is negative, it repels electrons, and hence the current flowing in the grid circuit is negligible. For this reason the grid power, which is the input required to operate the valve, is also negligible. It is thus possible to control a large amount of power in the anode circuit by an extremely small power in the grid circuit. Not only does this enable an effect to be amplified, but it does so without reducing its magnitude. For example, a triode amplifier may be connected via suitable electrodes
to a nerve or muscle preparation without disturbing its normal function.

The use of the triode as a power amplifier is shown in figure 3(a). The alternator represents the source of the effect to be amplified. It is connected between grid and cathode of the valve in series with the battery which serves to set the valve at its correct working point. Clearly voltage variations in the grid circuit will produce corresponding current variations through the recorder in the anode circuit, and the waveform of the variations will be preserved for future reference. Here the recorder in the anode circuit acts as a "load" of low resistance which requires appreciable current but only a small voltage to operate it. At other times, however, the triode amplifier must feed a device of high resistance, such as another valve or a cathode-ray tube. Here high voltage at low current is needed, and this is obtained by allowing the anode current to flow through a high value resistance as in figure 3(b). The varying anode current then produces a varying voltage drop across the anode load and this is fed to subsequent valves, etc. Used in this way the triode is behaving as a voltage amplifier, the "gain" of the amplifier being the ratio of output to input voltage change. It is, of course, possible to connect voltage amplifiers together so that the output of one forms the input of the next, and very high values of gain are then possible.

Although the above amplifiers have employed triodes, even more complex valves with extra electrodes are commonly encountered. These are called tetrodes, pentodes, etc., but they will not be discussed specifically as their behaviour is similar in principle to that of the triode.

In the above discussion of the use of the triode as an amplifier it has been assumed that the characteristic curve is linear and unchanging. In practice, however, the characteristic is always curved, and this results in distortion of the output voltage or current waveform. Moreover ageing of the valve and its associated components and alterations in supply voltages cause changes in the performance of the system. It is therefore very desirable to use valves (and transistors) in such a way that the over-all characteristics of the system are substantially independent of such imperfections in the components.

There are two methods of achieving this end, and it is interesting that the human body makes use of very similar methods to stabilize its behaviour and to render it independent of changes in its components. The first is applicable directly to amplifiers, and is known as negative feed-back. In principle it operates by automatically comparing a fixed fraction of the amplifier output with its input, and if any discrepancy exists a correction is made. These operations, of course, occur simultaneously and their speed is limited only by the speed of electrical processes. In a very similar manner, voluntary muscular movements in the body may be inspected visually or otherwise, and the result of the inspection is used by the brain to apply a correction to the original movement if it is inadequate or exaggerated. A very simple way of applying negative feed-back in a valve amplifier is to insert a resistance in the cathode circuit, e.g. at X in figure 3(a). If then the anode current of the valve is too large, the cathode will be more positive than normal and this is equivalent to an increase of negative potential on the grid with respect to the cathode. The anode current is therefore reduced. Negative feed-back always results in a reduction of gain, but this is accompanied by an increase in linearity and stability which would be almost impossible to achieve by any other means.

The second method cannot be applied directly to the stabilization of amplifiers. It finds its main application in the conveying of information of one sort or another, and in principle is similar
to the mechanism of nervous conduction, in which a train of impulses of variable frequency characterizes the information to be conveyed. In the electronic analogue valves are used simply as switches, the anode current being turned on and off by making the grid alternately positive and negative. This "valve switch" produces voltage or current pulses, and it is clearly unimportant if the characteristics of the valve change even by a large amount. Radar is a very well-known example of this pulse technique, which is in fact responsible for its great reliability.

We have discussed how valves may be used for linear amplification, but if the characteristic is grossly non-linear the output waveform can differ from the input in almost any desired manner. This is often useful when one type of waveform is available and another is desired.

Valves, however, can also be used for producing specific waveforms. Let us consider a simple triode amplifier with an alternating voltage input producing an output of identical waveform at a much higher energy level. If we simultaneously remove the input and replace it by an identical voltage obtained from the output, the valve would continue to deliver its original output but in the absence of an external input. It is then converting energy from the anode battery into energy of the desired waveform. In practice the waveform so obtained would rapidly degenerate, and it is necessary to have an auxiliary circuit to maintain its shape.

Figure 4 shows a triode arranged to produce a sinusoidal output. The inductance and capacity

in the input form an oscillatory circuit, which briefly is the electrical analogue of a mechanical vibrating system. Thus if an electrical impulse is given to the circuit, a sinusoidal oscillation will be produced which in the absence of the valve would die away rapidly due to the conversion of electrical energy into heat. In a similar manner the oscillations of a mechanical system will decay due to frictional losses. The alternating voltage produced across the oscillatory circuit, however, is amplified by the triode in a more or less linear fashion, and part of the output energy is fed back to the grid circuit by magnetic coupling. The feedback in this case is positive, because it is in such a direction that it assists the original input. In this way the energy lost in the input circuit is replaced from the output, and the whole circuit "oscillates" continuously. This basic circuit is used clinically for the production of high frequency alternating currents in "short wave" diathermy.

If, on the other hand, the valve is used merely as a switch, usually in conjunction with a second valve instead of the oscillatory circuit, pulses will be produced. The well-known electronic muscle stimulator operates in this way.

The cathode ray tube.

Before concluding our review of the basic electronic devices and their applications the cathode ray tube must be mentioned as the most important and universally applicable display device. If for example we have a pressure transducer operating into a linear voltage amplifier, the output will consist of a varying voltage, whose waveform is an accurate representation of the original pressure variations. If these variations occur rapidly, as they would in the cardiac cycle, it would be impossible to observe and record them with the unaided senses. The cathode ray tube is a device which will display the waveform as a graph of voltage against time, and the trace so obtained may be viewed, traced or photographed as required. Moreover, the speed of the device is limited only by the inertia of the electrons, which sets an upper limit of the order of several thousand million cycles per second.

Figure 5 shows a cross-section of the cathode ray tube including only the essential features.
Enclosing the whole is a glass bulb flared at one end and thoroughly evacuated. At the small end a heated cathode emits electrons and these are accelerated by an electrode system similar in principle to the triode. The assembly is known as the electron gun, because it produces a beam of electrons which travel down the axis of the tube and strike the end face. This internal surface is coated with a material which fluoresces under the impact of electrons and as a result a small luminous spot is produced which can be viewed from outside. The brightness of the spot may be controlled by varying the potential of the grid in the electron gun. This luminous spot acts as the writing point, and next it must be deflected so as to trace a pattern on the screen. This is done by including two pairs of plates between which the beam must pass, known as the deflector plates.

If a potential difference is applied, for example, to the Y plates (see fig. 5(b)) the beam will be deflected vertically, i.e. along the Y axis. Similarly a horizontal deflection may be obtained by the use of the X plates.

To examine a voltage waveform the latter (referred to as the signal) is applied to the Y plates and a voltage of saw-tooth waveform to the X plates. The latter causes the spot to move from left to right across the screen at the required speed, and then to fly back rapidly to its starting point. This process may occur periodically if desired. At the same time the signal is producing a vertical deflection, and the result of both processes is the appearance of the desired waveform on the screen. If the X deflection, or time base, is periodic, it can be arranged that successive patterns all coincide on the screen thus giving the illusion of a stationary waveform.

The cathode ray tube possesses similar advantages to the thermionic valve. Its speed is for practical purposes unlimited and as the deflector plates take virtually no current from the source, the waveform observed is a true representation of the original effect.

There are, of course, other methods of displaying and recording waveforms, but as these are not peculiar to electronic systems, they will be dealt with in connection with their special applications.

(To be concluded)