The Role of Platinum Metals in Neurological Prostheses

PROGRESS IN BIOMEDICAL APPLICATIONS

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Prostheses are devices for restoring artificially some function lost through accident or disease. Neurological prostheses, therefore, are surgically implanted microelectronic devices which seek to ameliorate the results of neurological defect. Examples are: implants for treating incontinence, or for recovering some use of paralysed arms and legs following spinal accident; implants for patients who are blind as a result of damage to the eye or optic nerve; implants for patients who are deaf as a result of damage to the inner ear. In addition, there are some implanted devices which are not strictly prostheses; for example, implants for relieving pain, and implants for correcting curvature of the spine in children. Despite the variety of purposes for which neurological prostheses are built, they have in common that they are all nerve stimulators and can all be realised using, substantially, the same technology. This article discusses the technology for implant-making which has been worked out at this Unit, and shows the essential role played by noble metals in that technology.

That electric currents have an effect upon the nervous system is one of the oldest observations in electrical science. Chapter One of practically any general textbook of electricity has something to say about Aloisio Galvani (1737–1798), and his experiments with frogs' legs toward the end of the eighteenth century. At about the same time, people were giving themselves, and each other, shocks from frictional electrical machines and charged Leyden jars; it was clear that both motor and sensory nerves were affected. An important question arose; were electrical effects factitious, or were animals—including humans—actually some kind of electrical machine? The shocks one could get from electric fishes pointed toward the latter view, but electric fishes might be a special case. In 1842, Matteucci performed a classic experiment which first demonstrated "secondary contraction": two frog nerve-muscle preparations are dissected out, and the nerve of preparation **B** is laid alongside the muscle of preparation **A**. When nerve **A** is stimulated, by pinching, **both** muscles instantly contract. Because the effect on **B** is immediate, the influence can scarcely be chemical, but is almost certainly electrical. Here was good evidence that the action of ordinary muscles was indeed, in some way, electrical in nature.

Notice the use of preparation **B** as an instrument for detecting the feeble electrical effects shown by preparation **A**. It was to be many years before man-made detectors could match in sensitivity the frog preparation. Eventually they did, however, and when they did, they gave quantitative determinations, were stable, and could be calibrated. They established that nerve fibres also propagate something electrical in character, the so called "action current". Milestones on the way to these sensitive detectors were the capillary electrometer (1872), the string galvanometer (1901) and the valve amplifier with cathode-ray-tube display (from the year 1919 onwards).

Over a period of some 150 years, then, a great body of electrophysiological knowledge was accumulated. By 1950 the biophysics of nerve could be said to be understood, and before long, many laboratory neurophysiological experiments could be regarded as complex interactive processes between the apparatus—perhaps under computer control—stimulating, and recording action currents from, various points in the nervous system of the anaesthetised animal under investigation. Very occasionally, perhaps as a result of the need to carry out a particular surgical procedure, the nervous system could be human.

The transfer of electrophysiological know-how from research environment to clinical application, in the form of neuroprosthetic implants, had to await the invention and development of the transistor. This is not because such implants contain transistors. They need not; one can make extremely useful devices without employing transistors. It is rather that the availability of transistors forced manufacturers of associated electronic components to miniaturise their products, so that the beneficial reduction in equipment size, weight and power consumption, which the transistor offered, could be fully realised. Hermetically encapsulated transistors were available by the mid 1950s, and the accompanying range of companion passive components soon followed. The first neurological prosthesis, the fixed-rate cardiac pacemaker, was announced by two separate groups, one Swedish and one North American, in 1959. It is rather reassuring to find that this important medical-technological development could not have occurred much earlier than it did (1,2).

Other prostheses soon followed: the phrenic nerve stimulator, for patients who cannot breathe on their own, in 1966 (3) and Brindley's first visual prosthesis in 1967 (4). Since then the subject has grown enormously, with cardiac pacemakers, phrenic nerve stimulators, cochlear stimulators for the deaf, spinal anterior root stimulators for the incontinent and dorsal horn stimulators for those with chronic pain, all commercially available. This Unit, directed by G. S. Brindley, F.R.S., was founded in 1968. It is not primarily a clinical unit; its task is to develop implant applications and implant technology generally.

The Nature of Neurological Prostheses

Ideally, a prosthesis would be a "fit and forget" device, wholly implanted. No training would be needed to use it, and the patient would not appear disabled. Viewed as a bridge for crossing a damaged section of nervous tract, the ideal prosthesis would record nervous activity somewhere upstream of the lesion, and stimulate appropriately healthy nerve fibres somewhere downstream. At present only the demand pacemaker has these ideal features. Most prostheses, though contributing to the quality of, and possibly extending, the patient's life, fall short of the ideal. For example, a paraplegic with an implanted leg-controller has at present to manipulate controls on a box, perhaps attached to his belt. The box sends commands to an implanted radio receiver, which decodes them and sends suitable pulses of stimulating current along flexible cables to electrode groups maintained in near contact with the relevant motor nerves. This patterned stimulation in turn causes muscles in the hips and legs to contract and relax as required. Confining myself henceforward to prostheses designed and built in this Unit, we see that in general they divide into an external and an implanted part, and that the implanted part divides again into receiver block, cable, and electrode group. In all three implanted parts, noble metals find application.

Electrode Groups

Electrode groups can be monopolar, bipolar or tripolar. The pattern of the current flow around each is shown in Figure 1. In principle, the tripolar group is best, since the current is largely confined within the group; thus there is minimal stray current to disturb neighbouring structures such as sensory nerves, whose unintended stimulation may be experienced as pain. On the other hand, tripoles are evidently

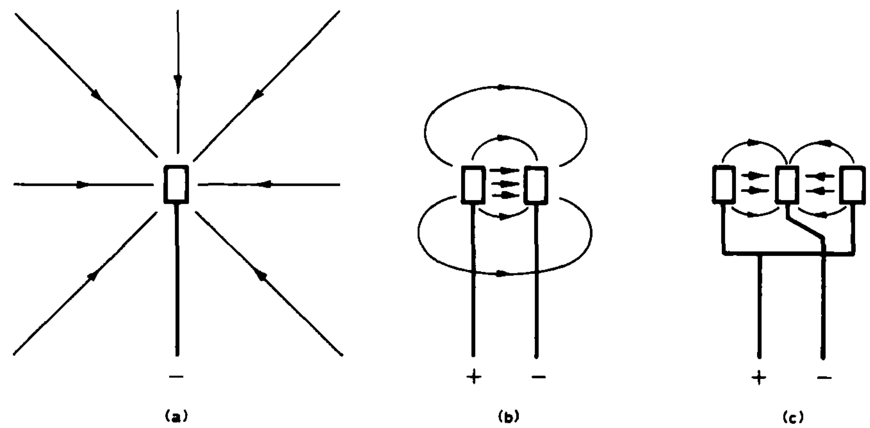

Fig. 1 The pattern of current flow about (a) monopolar, (b) bipolar and (c) tripolar electrode groups, indicating the extent of current spread

the most elaborate, and in cases of difficult surgery may be hard or impossible to place correctly. When access to the nerve is very awkward, it may be that the best that can be done is to get a monopole in as nearly the right place as possible. Our electrodes are invariably of platinum, to which some iridium may have been added where springiness is desirable. The task of the electrode is to convert an electron current in the metal, to an ion current in the extracellular fluid, with acceptably low overvoltage and by redox processes only; while so doing, to dissolve as slowly as possible, forming dissolution products of minimal toxicity; to be convenient in fabrication and easy to join to other materials. Platinum performs these tasks admirably. The redox charge-injection capability is about 300 microcoulombs per real (as opposed to projected) square centimetre of surface (5,6), which we consider sufficient. The dissolution rate is about 30 nanograms per coulomb if the electrode is properly used (7), which implies a satisfactory life. Pure platinum is easy to handle, platinum-iridium rather less so. Either metal is easily joined by brazing with gold. Figure 2 shows a form of tripolar group devised by Brindley (8); the electrodes are U-shaped and line a trough, fabricated from silicone rubber, into which the nerve is lowered. It is then loosely trapped by snapping onto the trough a silicone-rubber lid.

Implantable Cable

An implantable cable must conform to movements of the patient's body, and so must be able to bend, twist, stretch and resist crushing. It should comprise several separate

Fig. 2 This end view of a tripolar electrode group shows the U-shaped platinum electrodes lining a silicon rubber trough where the nerve is placed

conductors, to the ends of which temporary or permanent connection can be readily made. A form of cable which meets these requirements has been devised by J. D. Cooper (9). The body of the cable is of silicone rubber, 2 mm in diameter. Through this pass between one and five intercalated helices of 20 per cent iridium-platinum; the wires are 75 microns in diameter and insulated with a polyimide resin. Two short lengths of cable are shown in Figure 3. We usually have one end of the cable permanently attached to its electrode group by gold brazing; the other end terminates in an implantable plug-and-socket assembly, known as a Craggs connector (10). Cooper cable has proved extremely reliable in use, and we attribute much of this to the excellent mechanical properties and resistance to corrosion of the alloy used.

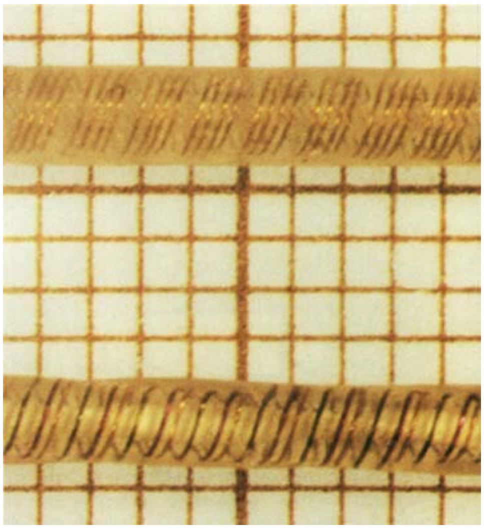

Fig. 3 The Cooper multiconductor iridium-platinum cable is able to withstand bending, twisting, stretching and crushing, so conforming to the movements of the patient's body. The lower of these two pieces of four-cored cable is an experimental length with colour coded conductors. The sides of the background squares measure 1 mm

Receiver Blocks

Receiver blocks vary greatly in complexity, from those which are virtually miniature crystal sets, feeding to a single electrode group stimuli derived by rectifying a simple modulated carrier wave, such as that shown in Figure 4, to complex demultiplexing receivers supplying several electrode groups from few, possibly only one, radio signal. Whether the receiver is simple or elaborate has, however, little influence on a fundamental decision in implant design, which is, what sort of metal should the electrical conductors be made of?

Suppose we have been asked to encapsulate a cylindrical torch battery, having an insulating body and a pole at each end, in some rubbery or resinous material so that, upon being thrown into the sea, it will not discharge. Water vapour will diffuse through the encapsulant and will condense into any voids at the interface between encapsulant and battery, particularly if

Fig. 4 An implantable block of three simple receivers and a triplet of Craggs connectors, on the left, shown here at approximately full size. Each of the receivers will supply its own electrode group

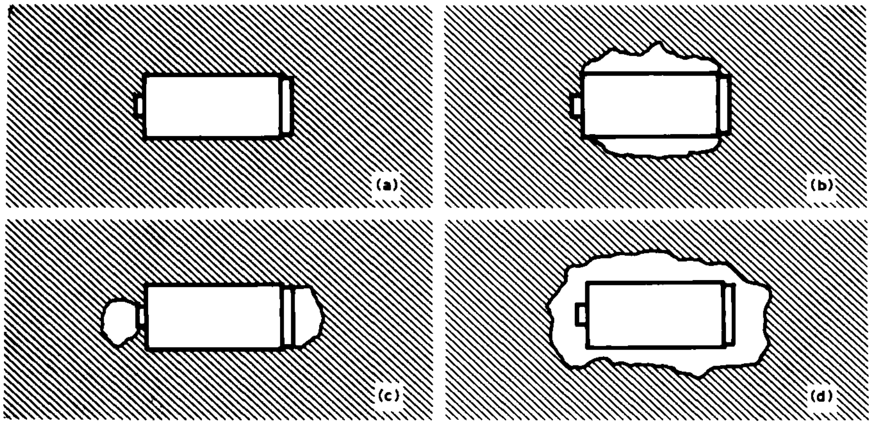

Fig. 5 If a cylindrical torch battery with an insulating body and a pole at each end is encapsulated in a supposedly adhesive but unavoidably water-vapour-permeable material and then immersed in water, a number of things may happen. Of the four situations shown here, only condition (d) is disastrous, the battery having been discharged

this interface is contaminated with water-soluble soil. If, after a week or two, we go and retrieve our battery, we might find one of four things has happened: (a) The encapsulant is everywhere adherent to the battery; the battery has not discharged. (b) The encapsulant is adherent to the poles but has become detached from the insulating body; the battery has not discharged. (c) The encapsulant is adherent to the insulating body but has become detached from the poles; the battery has not discharged. (d) The encapsulant is everywhere detached; the battery is discharged. These conditions are shown in Figure 5.

This illustration brings out an important general principle, which is that it is not necessary that the encapsulant adhere to both conductor and insulator surfaces, though clearly the resulting structure is stronger if it does. If we use a reactive metal such as copper for our conductors, we should be able to get the encapsulant to bond to it. But if, perhaps because of some carelessness in manufacturing technique, that bond fails here and there, the copper surface will become wet and corrosion will set in. Because corrosion products generally take up more space than the original metal, we can expect further adhesion failure caused by the pressure of accumulating corrosion products. Secondly, we might use a valve metal such as tantalum; it is tempting to use the surface oxide film on tantalum wire as the insulation, and good adhesive bonds can be made to the oxide surface. However, if nevertheless some local failure of adhesion should occur, there are circumstances in which the oxide layer could be electroreduced, with consequent malfunction of the implant. The third option is to use a noble metal, accepting that the encapsulant will not bond to it, so the metal will operate permanently wet. To minimise the mechanical weakness resulting from the absence of adhesion, one uses an insulator to which excellent adhesion is possible, and lays out circuits so that the area of insulation presented to the encapsulant is large compared with the area of the conductor.

In our Unit we have concentrated on the third option. Circuits are made by thick film technology; the insulator material is consequently alumina; an example is shown in Figure 6. For the conductor pattern we use a fritted gold-platinum alloy and the terminal posts are 18 carat gold, while the coils can be wound from silver wire. Chip capacitors and resistors have silver-palladium terminations.

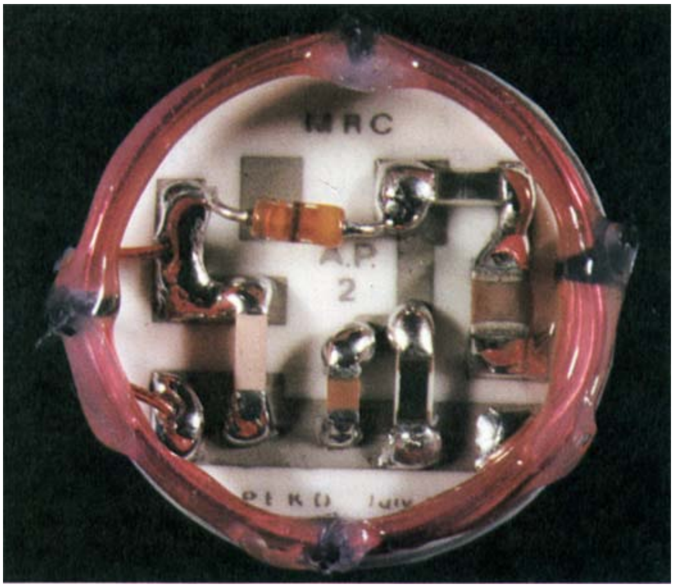

Fig. 6 This simple thick-film receiver for an auditory prosthesis incorporates a number of noble metals. The gold-platinum conductor pattern leaves a significant area of the alumina exposed, where the encapsulant can adhere firmly, so providing the required mechanical strength

Diodes and transistors present a slight problem: these components can be obtained with gold-plated "Kovar" leads, and it is tempting to use them. Unfortunately the amount of gold used is not really sufficient for implant use, and the smallest pinhole will lead to serious corrosion of the underlying iron alloy. We have found it advisable to switch to option one here, and use components with tin-plated leads. Manufacturers can afford to be more generous with tin, but if one has any reason to suspect they have not been, one can always add more when soldering the component in. Lastly, there is the matter of the solder itself. We use a tin-lead eutectic solder with 2 per cent added silver, which works well in practice. We are careful always to be generous when soldering, so that if, by some mischance, there should be an adhesion failure nearby and corrosion of the alloy sets in, there is plenty of sacrificial anode underneath, to hold the joint together.

Conclusion

Noble metals have an essential role to play in neurological prostheses. In all applications their chemical inertness and ease of microjoining are invaluable. In addition, the good fatigue resistance of iridium-platinum alloy makes possible very satisfactory implantable cable, while the redox performance of platinum and iridium-platinum electrodes in saline allows one to stimulate nerves artificially for long periods, and as yet we do not know just how long, without harming them.

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