NERVE GRAFTING

Watson-Jones Lecture delivered at the Royal College of Surgeons of England
on
10th January 1963
by

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For the first time in my life I find myself delivering an eponymous lecture in the presence of the eponym—only a shade less embarrassing than for a man having to deliver a lecture named after himself. This is what happened to Dr. Wilder Penfield in Beirut in the spring of 1961; he felt, he said at the time, a little posthumous. I mention this, Mr. President, simply as a suggestion for your consideration when choosing a later Watson-Jones lecturer.

No matter what the occasion, I always feel that giving a lecture in this College, perhaps no more than one in a teaching series, is an honour and, at any rate for the lecturer, a stimulating experience. It is particularly so to-day. We are celebrating the distinction of Reginald Watson-Jones. In spite of what I have just said, I like this. The Indian ceremonial garland hung round the neck of someone, someone living, whom the hospitable people of that country wish to honour is far better than the elegant wreaths we lay on the grave of a departed friend.

I shall not cause Sir Reginald to blush by reciting all his achievements, but I must mention one which, above all others, is imperishable. His great book on fractures may one day be out of date, though not in my time. But this cannot be said of a scientific journal, which has a particular kind of immortality. Its past volumes gradually become woven into the fabric of scientific knowledge; its current numbers reflect new patterns of thought and practice. It was Watson-Jones more than any other man who, as its Editor, has given us the British half of the *Journal of Bone and Joint Surgery*. It is a splendid feature of this venture, unparalleled at the time of its inception, that, with the Americans, we have one journal for orthopaedics for the whole of the English-speaking world.

I turn now to the theme of this lecture, nerve grafting.

I propose to deal almost exclusively with the repair by grafting of injured nerves in the limbs. This has been the subject of serious study for some 20 years in this country, and the time has come to enquire whether this operation is a toy or a valuable surgical weapon.

Nerve grafting emerged from the First World War with a thoroughly shady reputation. When the Second War started we had to ask ourselves whether the unsatisfactory results had been due to what might be called biological futility or, on the other hand, whether nerve grafting was theoretically sound but had failed because of imperfections of technique. There had been a few encouraging developments between the wars. Grafting of the facial nerve in the middle ear had been developed by Ballance and Duel and had become a standard operation in Britain thanks largely to the work of Josephine Collier. Bunnell and Boyes had reported good results from grafting of injured digital nerves and had had some success with grafts of the larger nerve trunks in the limbs. On the face of it there was a case for making a further attempt, and at Oxford a strong team of zoologists carried out an elaborate series of experiments. It was a rare privilege in those days to work with J. Z. Young, P. B. Medawar, F. K. Sanders and William Holmes. The conclusions they arrived at were these. Heterogenous grafts behave as foreign bodies and are completely useless. Homogenous grafts provoke a brisk cellular reaction, but, nevertheless, are capable of conducting outgrowing axons to the periphery. They are nothing like so satisfactory as autogenous grafts which, in the experimental animal, lead to recovery little inferior to that following end-to-end suture of a nerve.

Encouraged by these findings we cautiously set about grafting a few nerves where no alternative form of repair was possible. Autogenous grafting was clearly the first line of attack, but we used homogenous grafts in four cases where autogenous material was insufficient for bridging a very large gap. These homogenous grafts were a complete failure, and Barnes and his colleagues at Winwick had exactly the same experience. There was a discrepancy here between the experimental findings and their clinical application. Medawar's work, which ultimately earned him the Nobel Prize, provides a possible explanation. Thanks to him we are all familiar with the phenomenon of acquired immunity in relation to the transplantation of skin and of other tissues. You will recall that it takes some time for this immunity and the reaction consequent on it to develop. If a short graft had been used to bridge a gap in a nerve—and those employed experimentally were often about 2 cm. long—the graft could and did act as a bridge for the outgrowing axons, which were able to reach the distal stump before the immune reaction destroyed the graft. But in clinical practice no-one would ever use a homogenous graft only 2 cm. long; a gap as small as that can always be closed by an autogenous graft. In our four cases of homogenous grafting we used strands of nerve ranging in length from 11 to 19 cm. If the immune reaction provoked by nerve tissue is anything like that produced by skin then it is clear that with grafts of this length the storm breaks long before the out-growing axons have reached the other side. This is precisely what happens.

So we were driven to the conclusion that autogenous grafting was the only method likely to offer a reasonable chance of success and we have stuck to it. The drastic measures that can be used to suppress the immune reaction hardly seem warranted in this field of surgery.

There is, however, another significant difference between experimental nerve grafting and what is sometimes required in clinical practice. Although the small nerves used in certain types of operation are comparable with, say, the sciatic nerve of the rabbit, a serious problem of survival arises if we use grafts taken from one large nerve to repair a defect in another. During the war and since, we have regularly encountered cases in which extensive destruction of two nerves (or more) has occurred and it is then reasonable to take material from one to make good the gap in the other. It has been supposed that the length of a graft is significant, but unless a graft is revascularized almost solely from its junctions with the

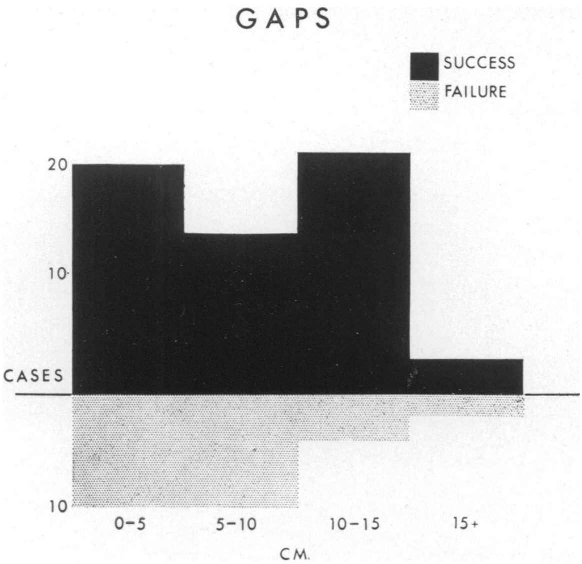

Fig. 1. This diagram illustrates the extent of the gaps repaired. The grafts were all about 15 per cent. longer than the gaps in order to allow for shrinkage. The results are based on 83 nerves because 26 cases of digital nerve grafting have been excluded as too complex for satisfactory representation. Successes and partial successes have been run together.

recipient nerve, there is no reason why this should be so; and, as it turns out, long grafts are as likely to succeed as short ones (Fig. 1). What matters far more is diameter. Is a large graft more likely to undergo necrosis or collagenization than a small one? A graft taken from a main nerve trunk in a limb is a substantial piece of tissue.

On a number of occasions I have explored damaged radial nerves and found gaps too great to permit repair; the usual flexor-to-extensor tendon transplantation was the only remedy. In some of these cases it was expedient to carry out this palliative operation at a later stage, and this gave me the opportunity to sever a length of nerve from the proximal part, reattaching it immediately or laying it free on the surface of a muscle, and then recovering the specimen at the time of the second operation. The piece of nerve was in the same state as a free nerve graft. Abnormal histological changes were always found. The normal appearances would have been those of Wallerian degeneration, that is, brisk phagocytosis of axis cylinders and myelin and proliferation of Schwann cells. The abnormalities were of three kinds:

(i) Delay in removal of the axis cylinders and myelin.

(ii) More or less interstitial collagenization, in places of a degree sufficient to obliterate the Schwann tubes that, in a nerve graft, are the essential channels which conduct the outgrowing axons to the periphery.

(iii) In the one case in which a graft taken from the proximal part of the lateral popliteal nerve (along with one taken from the distal part of the same nerve) was used to bridge a large gap in the medial popliteal nerve, exploration 17 months after the repair revealed that the graft was dead; there was not even any collagenous replacement.

These findings indicate that a nerve graft of considerable calibre does not behave in the same manner as the distal segment of a divided nerve. The necrosis shown in one case was catastrophic; no new fibres could have penetrated the necrotic graft and from this it is evident that, at any rate in an adult, a piece of normal lateral popliteal nerve is too thick to survive transplantation. Wallerian degeneration is an extremely active process; there is ample evidence that in a thick graft it is retarded, presumably because the nutrition of the graft is grossly subnormal. The collagenization I have mentioned is very similar to that seen in ischaemic nerve damage, and it is reasonable to suppose that in these grafts inadequate or tardy revascularization is the reason for it.

Are there any ways in which we can aid the survival of a graft of large calibre? Years ago there was much controversy about the value of what were called pre-degenerate grafts, that is to say, grafts that had been allowed to undergo Wallerian degeneration before transplantation. No very clear answer emerged, but the results of an observation I am going to describe suggest that the graft is more likely to survive if it is degenerate.

You will recall the patient I described with extensive damage to the sciatic nerve. One piece of the proximal part of the lateral popliteal nerve and another taken from the distal part of the same nerve were used to bridge the gap in the medial popliteal—which has about twice the cross-section area of the lateral popliteal nerve. This patient did not show signs of recovery at the expected time and for this reason I explored the nerve and removed two minute pieces, one from each graft. The specimen from the graft that had not degenerated before transplantation revealed necrosis, whereas that taken from the pre-degenerate graft was permeated by new nerve fibres indistinguishable from normal regeneration. And there was some recovery in the calf muscle subsequently, which must have been through the pre-degenerate graft. It is reasonable to suppose that a degenerate nerve has much more modest metabolic requirements than the distal part of one that has just been severed and from which the myelin

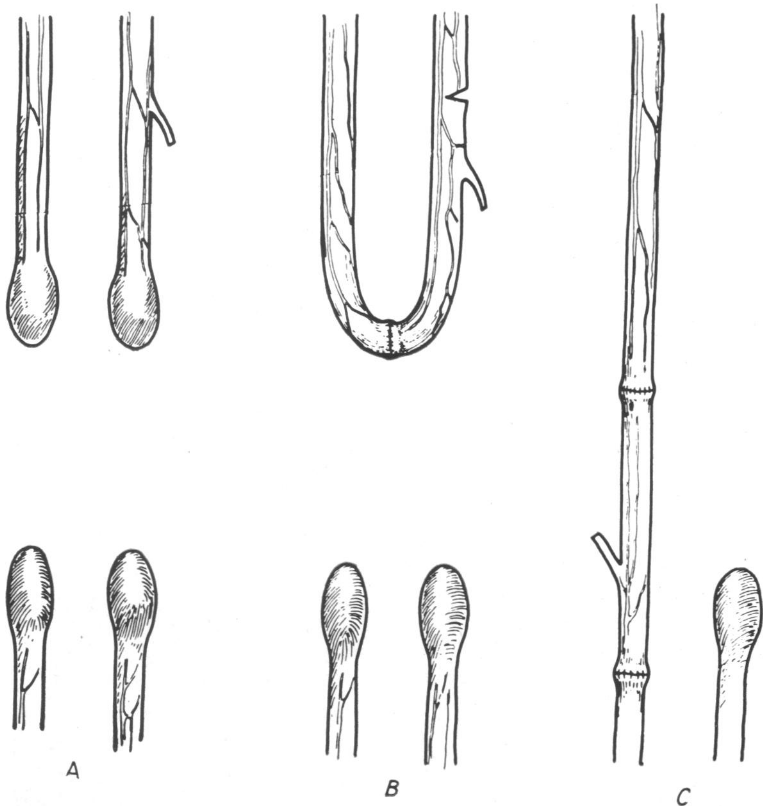

Fig. 2. The two steps in the nerve-pedicle operation. After resection of the end-bulbs the median nerve (left) is sutured to the ulnar (right); the latter is cut across or ligated at an appropriate level, but without disturbance of the longitudinal blood vessels. The second stage is carried out six weeks later, at which time it is not unusual to find that the detached end of the graft oozes blood.

and axoplasm must be removed by an intensely active phagocytic process. Unfortunately, to obtain a pre-degenerate graft is, in most circumstances, a surgical inconvenience of a high order. Fortunately there is a better solution.

The nerve-pedicle operation (Fig. 2), the aim of which is to conserve the blood supply of a thick nerve graft, in much the same way as with a skin pedicle, was first performed by Barnes and his colleagues in 1945, was conceived independently by St. Clair Strange and described by him in 1947. In this operation the graft is dealt with in such a way as to conserve its blood supply, and Wallerian degeneration occurs as a result of section or ligation of the nerve. This excellent operation has stood the test of time.

Let us now look more closely at the circumstances in which a number of most able surgeons arrived at their adverse verdict at the end of the First World War. Sepsis was their bugbear and, thus, the nerve grafts probably lacked the well-vascularized beds essential for their survival. Secondly, the fact that grafts shrink was then unknown and it is possible that separation occurred at one end or the other. Lastly, and perhaps most important, single strands of cutaneous nerve were used to bridge gaps in major nerves, which set a strict limit to the number of fibres that could be conducted from the centre to the periphery. The diameter of a nerve graft, or assembly of grafts, must be the same as that of the recipient nerve. It was possible, therefore, that with far better methods for the control of infection at our disposal and with certain refinements of technique some success could be achieved.

During the Second World War—once it was certain that the experimental basis of nerve grafting was sound—it seemed justifiable to attempt the operation whenever end-to-end suture was impossible and the gap was not too great to be bridged with the autogenous material available. To-day more discrimination is necessary. The results of these earlier operations are known; we must define the conditions that make for success, and when these are absent the operation should not be done. In an experimental period it is, perhaps, justifiable for the irrepressible to pursue the unattainable, as has been cruelly said of another branch of surgery. Once that period is over, it is improper to subject a patient to an operation unlikely to do him any good, and we must not waste our own time either.

We have benefited greatly from what we learned about direct suture. The importance of reducing the interval between injury and repair is now generally appreciated, and in almost all of our cases nerve grafting was done well within the time-limits that we had determined for the successful outcome of ordinary nerve suture. We found that the results of repair of proximal lesions were far inferior to those of distal lesions, for reasons that must not detain us now; as a consequence of this we have avoided operations on the brachial plexus, except on the upper trunk where the distance from the spinal cord to the distribution of the terminal branches is much shorter than in the other two trunks.

The third major factor studied during the review of the results of nerve suture, the extent of the gap to be closed, has a special significance here. because it provides the main indication for nerve grafting.

The closure of gaps in injured peripheral nerves by mobilization of their trunks and suture with the appropriate joint flexed is now so firmly established in surgical practice that we easily forget that it was one of the great technical triumphs of the earlier years of this century. Because there was no reasonable alternative in sight surgeons spared no effort to get nerve ends together and this operation of closing the gap became a matter of international competition. And I need hardly tell you that the prize went to an American. So at the beginning of the Second World War, being good anatomists, we set about this technical exercise with great confidence. We closed large gaps, of up to 17 cm., without any tension on the suture line at all. But recovery did not occur at the expected time, and then we discovered that the heroes of the First World War had not related their results to the extent of the gaps closed. It became clear that for each nerve there was a critical resection length which in some situations was appreciably less than the gap it was surgically possible to close.

Here is an example. A man suffered a severe adduction injury of the knee that ruptured the lateral popliteal nerve. The gap after resection back to healthy nerve bundles was 17 cm., there having been, as always in traction injuries, extensive intraneural damage. It proved easy to suture the nerve with the knee three-quarters flexed. The joint was allowed to extend very gradually, and then the lateral popliteal nerve appeared as a tight cord, for all the world like the tendon of the biceps. There was never any recovery and subsequent exploration in this and in other similar cases revealed that the stretching of the nerve had produced extensive ischaemic damage, the intraneural collagenization being as severe as that caused by the original traction injury. We had produced a slower but not less devastating traction lesion.

It is possible to give figures for the " critical resection length ": this has been done for adults, but it is simpler and more logical to use a measure that is uninfluenced by stature. In general, it may be said that if the wrist has to be flexed more than 30 degrees, or the elbow or the knee more than 90 degrees the nerve will be endangered when free movement of the joint is permitted. Gaps requiring greater degrees of flexion for approximation of the nerve ends must be repaired, if it is possible, by nerve grafting. And of course much can be accomplished by reducing the gap by mobilization, using a graft to bridge what remains.

Another factor affecting the prognosis has emerged since we carried out our analyses for the Medical Research Council. It is the age of the patient; youth is on the side of good recovery and this is particularly the case for nerve grafts. By far the best of our results are in children.

Now let us consider the available material. It is of two kinds: cutaneous nerves that can be spared without appreciably upsetting the patient, and main-trunk grafts which can be used only when two or more main nerve trunks are damaged beyond hope of direct repair. The sources of the grafts are shown here (Table I) and the medial cutaneous nerve of the forearm emerges as the nerve of choice. I must emphasize that if any length of a cutaneous nerve is required it should be taken from the part proximal to its distribution. The lateral cutaneous nerve of the thigh and the small sciatic are unsuitable, because they are accessible only within their distribution and are giving off branches all along their length. Our favourite, the medial cutaneous nerve of the forearm, is resected between the elbow and the axilla, where there are no branches.

These grafts may be used in one of three ways, either as single strands, as in the repair of digital nerves, or as cables, where a number of strands are used to make up an appropriate diameter for repair of a large nerve, or as inlay grafts for repair of partially divided nerves. Suture of these small grafts is a fiddly and frustrating performance and it is far simpler to use concentrated fibrinogen which, when thrombin is added to it, forms a firm clot and secures the nerve ends very satisfactorily.

TABLE I

SOURCE OF MATERIAL USED FOR GRAFTING

Cutaneous Nerves:	
Medial cutaneous of forearm	51
Superficial radial	8
Sural	9
Others	4
Main Trunk:	
Ulnar	29
Half thickness median ..	8
Lateral popliteal	5
Radial	4
Others	4
TOTAL	122

Main-trunk grafts are of two kinds, either free or nerve-pedicle grafts. In spite of the disturbing observations I made earlier we have had successes with grafts taken from all the main trunks except the sciatic and its divisions. But the nerve-pedicle technique has given the best results of all. It is particularly valuable where the bed for the nerve is fibrotic, as in cases of Volkmann's ischaemic contracture, where the median and the ulnar may be extensively and irreversibly damaged by the ischaemia that has destroyed the muscle.

Table II shows, in summary, our results over a period of 20 years.

The factors influencing the outcome of nerve grafting are similar to those for nerve suture.

Delay. The operation ought not to be undertaken if there has been undue delay.

Proximal lesions. Repair of the brachial plexus has proved so disappointing that it should not be done except for the upper trunk alone.

Scarring. It is remarkable to find how little this matters. The ferocious scarring that inevitably follows prolonged sepsis is now largely a thing of the past, but even when it is pronounced there are ways—which we have exploited—of circumventing it. A scar can sometimes be excised; a scarred muscle may occasionally be folded in on itself so that the scar is buried; the nerve graft, which here has an advantage over end-to-end suture, may be laid in healthy tissue to one side of the scar—a by-pass operation—and, lastly, we may use a nerve-pedicle graft.

TABLE II

A. Cutaneous Nerves used as Grafts

	Failure	*Partial success*	*Success*
Digital	8	7	11
Others: single strand	3	1	3
Cable	9	4	9
Inlay	3	0	8

B. Main Trunk Nerves used as Free Grafts

	Failure	*Partial success*	*Success*
Upper limb	6	2	17
Lower limb	4	1	0

C. Pedicle Grafts—All Ulnar to Median

Partial success	5
Success ..	8

Age. Advancing years militate against successful repair of a nerve by grafting, even more so than in the case of nerve suture.

Insufficient material. The temptation to perform an inadequate operation, because the supply of grafts is insufficient, must be resisted.

The operation that emerges from this examination, which, I hope, is sufficiently objective, is a worthwhile procedure. Is there any possibility of enlarging the scope of its application? It is hard to say, but I can give some sort of an answer by describing three cases.

For three years after we had described the nature of the nerve lesions occurring in Volkmann's ischaemia of the forearm we had no thought, no hope, of being able to do anything about them. But the emergence of the nerve-pedicle operation provided us with the opportunity of repairing the median nerve at the expense of the ulnar, and the results of this operation have been good. We have even had some success with free grafts too.

But a hand remains a very inferior organ when there is complete ulnar paralysis, and after Volkmann's ischaemia there are usually no muscles to spare for the tendon transplantation that would restore the action of the intrinsic muscles of the fingers. Three years ago I wondered whether

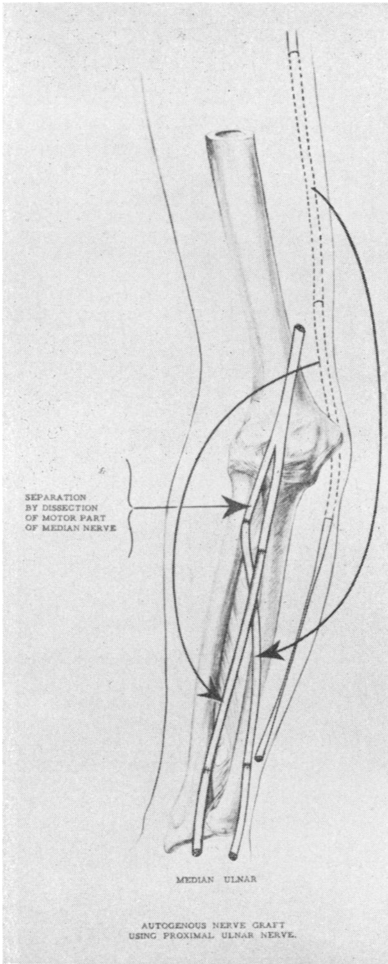

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Fig. 3. A method for restoring innervation to all the intrinsic muscles of the hand in severe Volkmann's ischaemia that has produced widespread damage of both the ulnar and median nerves.

we could use the motor division of the median just distal to the elbow which, because of the total destruction of the forearm muscles, is functionless as a source of motor fibres for innervation of the ulnar intrinsic muscles (Fig. 3). I carried out the operation on one child and then sat back and waited for the result. I had to wait a long time, but ultimately, to my great delight, he made a recovery not only in the motor and sensory distribution of the median nerve but useful recovery in the ulnar intrinsic muscles as well. I think now that I would be prepared to repeat this performance.

My second story. Where there is total brachial plexus paralysis, with no prospect of recovery, such as occurs all too frequently as a result of a traction injury—motorcycling being the greatest source of these crippling paralyses—the only available treatment is amputation through the arm with arthrodesis of the shoulder, followed by the fitting of a prosthesis. In those rather more favourable cases in which the upper trunk is less damaged than the rest of the plexus enough recovery may occur in the flexors of the elbow to permit the amputation to be performed through the forearm, which is much more satisfactory. Philip Yeoman and I wondered whether we could deliberately re-innervate the biceps and brachialis in a case of total brachial plexus paralysis that would otherwise be doomed to amputation through the arm. So, in November 1961, we carried out an amputation through the forearm in a particularly tragic case—the patient was an attractive girl of 17—dissected out the ulnar nerve from the elbow down to its bifurcation at the wrist and used it as a graft. The two terminal divisions of the nerve were joined to the third and fourth intercostal nerves after they had been exposed and severed; the graft was then led beneath the scapula to the axilla, where it was united with the musculo-cutaneous nerve. An arthrodesis of the shoulder was also performed. It is still a little too early to say how this is going to turn out, though now, just over one year after the operation, active flexion of the elbow is returning.

The last story is in a lighter vein. A certain Irishman had a superb voice and achieved great popularity by singing in public houses. One night his efforts so delighted his audience that in their ecstasy they threw the singer through a glass door. He was gravely injured, in fact, about one-third decapitated. His deep neck wounds were treated with great skill and shortly after they had healed I was invited to repair the tenth and eleventh cranial nerves. The severance of his vagus was serious; one vocal cord was paralysed, he could no longer sing and was in the depths of despair. I invited my colleague and friend, M. F. Nicholls, to lead the way into what was for me rather unfamiliar territory. He succeeded in finding the ends of the vagus. After resection there was a gap of 4 cm. which I repaired with two strands of a cutaneous nerve. In the fullness of time his voice returned, he could sing again and was once more a happy man. It is difficult in a hall of this size to give a convincing demonstration of the result of a nerve grafting operation, but the case of my Irishman provides what may be a unique opportunity. (A recording of the patient singing was then played.)

Alas, I can claim no credit for this. The patient's vocal cords were examined from time to time until, at last, it was reported that the paralysed one was moving again. But, on the day when the recording was made, a horrible suspicion chilled me. I had not known what the Irishman's voice was like before the accident, but as I listened to him talking to me I thought there was a husky quality in it. I sent him immediately to see our laryngologist, J. P. Monkhouse, and in a very short time he telephoned to say that the right vocal cord was still paralysed, but adducted. When we went into the whole business it appeared that the previous note was an error which he himself had *not* made. This little episode reminds us that a patient with a paralysed vocal cord can phonate well if the cord is firmly adducted. There is another point too and here may I take the liberty of addressing myself to the younger members of this audience. It is this, that in assessing the results of any form of treatment you cannot be too careful. From the data I have presented to you the records of all patients, many of them now living abroad, whose progress had not been followed for a sufficient length of time, or who could not attend for re-examination, were excluded. Hearsay evidence about the results of treatment in this instance, as in many others, is quite valueless. Check your results.

Lastly, you may ask me whether the favourable results reported can be obtained by any surgeon. The straight answer to this question is no, but they can be obtained by any man—or woman—who is prepared to acquire the necessary practice and is not too heavy-fisted. The operations were performed by a number of people. Every one of them was working in a hospital to which patients with nerve injuries were regularly sent, and so all had the opportunity to become familiar with the necessary methods of clinical examination and the refinements of technique, on which much depends.

We have long accepted the segregation of patients suffering from disorders of the brain and spinal cord amenable to surgical treatment. In my own field we have come to regard segregation as necessary for the proper treatment of hand injuries. I am persuaded that similar arrangements are desirable if injuries of the peripheral nerves are to be well treated, and I conclude by expressing the hope that in the re-organization of our accident services, which is likely to come to pass in the near future, this will not be forgotten.

There has been much detailed work in this survey and in the execution of it I am immensely indebted to my registrar, Malcolm Swann. I would also like to mention my long and happy association with my colleague, D. M. Brooks, whose elegant technique contributed so greatly to such success as we have had.