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SUTURELESS REUNION OF SEVERED NERVES WITH ELASTIC CUFFS OF TANTALUM*

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THE ADVANTAGES of using closely fitting sleeves as links between severed nerve stumps have been described previously.[5,6,7] The sleeves consisted of segments of artery, either fresh or frozen-dried and rehydrated. The experimental material on which the conclusions regarding the merits of the method were based included nearly 700 nerve unions in various animals (rat, over 500; rabbit, 21; fowl, 37; cat, 30; monkey, 81). Analytical studies of the healing and regeneration of nerves following sutureless splicing with arterial sleeves have demonstrated that the salient features to which this method owes its superiority are the following:[7]

(1) *Absence of Sutures.* This permits longitudinal traction to be transmitted directly from stump to stump through the tissue filling the gap, whereby the latter becomes converted into a system of parallel guide rails of strictly longitudinal orientation, over which the regenerating nerve fibers, sheath cells and blood vessels are then conducted into the distal stump without extensive branching, straying or confusion. The same longitudinal stresses turn invading connective tissue into an innocuous longitudinal course along the surface, thus preventing penetration of scar tissue into the space between the nerve stumps. Moreover, foreign body reactions, disorienting tissue whorls, and similar contingencies of sutures are precluded.

(2) *Confinement of Fluid.* A proper degree of liquidity of the tissue uniting the nerve stumps is prerequisite for nerve regeneration of optimal density. Liquid accumulates in the gap as a result of hemolysis, fibrinolysis, exudation from the nerve, and perhaps vascular transudation. The sleeve serves to prevent its dissipation.

(3) *Insulation and Protection.* The sleeve prevents adhesion between the nerve junction and the surrounding tissue, protecting the nerve against invasion by fibrous tissue and precluding the escape of nerve fibers.

Arterial sleeve-splicing shares feature (1) with the method of plasma suture,[4,8] feature (3) with many past and current procedures of nerve wrapping, but is unique in the combination of functions it serves.

It has been evident throughout this work that the clinical application

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of the principle of sutureless sleeve-splicing would be greatly facilitated if sleeves could be made from a material with physical and physiological characteristics similar to arteries, but more readily procurable. The success reported with the shielding of suture lines by tantalum foil[3] suggested that this material might be adaptable for the purpose.* This proved to be the case, as is illustrated in the following account.

METHOD

The problem was primarily a technological one, namely, to fashion tantalum foil into elastic cuffs of the caliber of nerves. Ordinary tantalum foil is highly pliable and unelastic. Unprotected exposure to heat makes it brittle. Yet, after some experimentation a heat treatment was finally discovered by which the foil could be molded into cylindrical rolls of the desired shape and resilience. The best results thus far have been obtained by the following procedure.

Tantalum foil, 0.00025 to 0.0005 inches thick, is wrapped around a cylindrical core which is to serve as heat conductor. The core consists of a central steel rod over which a fitting jacket of glass tubing is pulled. For each size of sleeve a matching size of core is used. The measurements of the foil are so chosen that it will cover two turns when rolled over the glass cylinder. Thin wire is wound around the tightly wrapped foil to keep it in place. The whole unit is then placed into an electric furnace for a specified period, the length of which varies with temperature, thickness of the foil, dimensions of the core and thermal properties of the latter, and must be determined empirically. A few seconds may decide the difference between success or failure. Underexposure leaves the foil unelastic, overexposure renders it brittle and useless. It will be noted that the inside of the foil is in contact with a heat conductor, while the outside is exposed to the radiant heat of the furnace.

When properly treated, the foil emerges from the treatment with changed properties. It has assumed the shape of a cylindrical coil of approximately the diameter of the core, has lost its pliability and instead become highly elastic. Owing to the fact that the outer turn has shielded the inner turn against direct heat radiation, the former turns out harder and more resilient than the latter. This gives the cylinder self-sealing capacity, inasmuch as the outer edge presses downward against the underlying turn, while the inner edge presses outward against the overlying turn. This asymmetry explains the fact that such a roll when forcibly uncoiled and allowed to recoil assumes the shape of an open spiral. To return it to its cylindrical shape, the originally inner edge must be tucked under the more highly curved outer turn. Each sleeve is to be allowed about one-half turn of overlap in its final form. This is achieved by trimming the outer edge.

Such sleeves are not only perfectly elastic, but have considerable structural strength. For instance, a tube, 27 mm. long and 3 mm. wide, made from foil 0.01 mm. thick, is able to withstand compression in the direction of its longitudinal axis up to 2000 g. without collapsing. After lateral compression by 700 g. pressure, it still resumes fully its cylindrical shape.

The sleeves must be chemically clean, for impurities along their surface would provoke tissue reactions.

In using these sleeves for the joining of nerve stumps or for junctions between nerve stumps and grafts, it has proved more convenient to treat them as tubes in the manner previously described for arteries, rather than by uncoiling and recoiling. One may use either a modification of the arterial splicing clutch[6] or adopt the following simplified procedure.

A bevelled thin-walled metal or glass canula, slightly wider than the nerve stump, is at-

* I owe my acquaintance with this material to Major W. P. Van Wagenen, M.C., A.U.S.

tached to a saline-filled syringe. The sleeve, slightly distended, is pulled over the canula. The nerve end is placed on the bevel, eased into the orifice, and finally sucked farther in by raising the plunger of the syringe. The sleeve can then be easily slipped from the canula onto the nerve stump, whereupon the nerve end is extruded from the canula by depressing the plunger. An air aspirator may be used in place of the syringe.

In the absence of special equipment, any hollow cone wide enough at its base to hold the nerve stump can be used as an aid in sliding the metal sleeve over. The width of the sleeve should be so chcsen that it will fit the nerve closely without tightness. Elasticity and overlap allow for adjustment to local conditions. The length of the sleeve will vary with the requirements of the individual case, particularly the location of the lesion and the extent of nerve adhesions.

The actual linking of nerve stumps which can be approximated to within several millimeters is done as follows. The sleeve which is to serve as link is pulled to full length over the distal stump. In order to facilitate handling of the proximal stump, a shorter tantalum cuff of corresponding diameter is pulled over the proximal end, its rim flush with the cut surface. The longer sleeve is then pulled back from the distal stump and telescoped over the cuffed end of the proximal stump, as in the joining of two stovepipe segments. The grip of the sleeve on the nerve ends may then be tightened by a gentle wrapping movement or by a loop of silk drawn around it and left in place until coagulating blood which has seeped between the overlapping edges has sealed the tube. No further means of attachment are necessary if the sleeve is of sufficient length. Nerve ends in a well-fitting sleeve act like pistons, and the suction which their separation creates tends to hold them in place. The fact that moderate tension can thus be tolerated without risk of rupture of the link, is a major factor in the success of the ensuing regeneration process.

A gap of several millimeters between the nerve ends has been found quite acceptable. The maximum tolerable length compatible with good regeneration remains to be determined. Where force becomes necessary to bring the nerve ends within range, it should not be applied at the ends or within the sleeve, but at more remote levels; for instance, by a sling stitch of tantalum wire looped through both stumps well above and below the sleeve region. This loop should take up only the excess of stress, but must not be shortened to a degree where it would leave the nerve ends in between slack.

Spider monkeys and cats were used for the experiments. Peroneal and tibial nerves severed in midthigh were reunited with tantalum sleeves. The animals received only a thin coat of synthetic resin over the skin suture, but neither casts nor splints. Their movements were in no way restricted. Eight nerve unions were performed in monkeys, and twelve in cats

RESULTS

Five monkey and six cat unions have thus far been examined, the oldest seven weeks after the operation. In none of them had the nerve stumps pulled loose in spite of the unrestrained exercise of the animals from the very first day after the operation. Only in two of the earliest cases had the sleeves crumbled, evidently owing to inexpert handling. In all other cases, the sleeves had remained unchanged.

There were no or only very slight adhesions between the nerve and the wound bed. A continuous fibrous nerve sheath was present. After its dissection the tantalum sleeve, covered by a very thin, smooth, transparent membrane, came into view. The ends of each sleeve had become walled off by rings of connective tissue continuous with the epineurium, undoubtedly due to the chronic irritation set up by the sharp rims. However, since these scars formed at a safe distance from the nerve gap, did not penetrate into the nerve, and had not given rise, at least not at this stage, to lateral adhesions, they do not seem to present a serious hazard. After slitting the thin cover membrane, the sleeve was grasped by its overlapping edge and stripped off, or rather unwound, from the nerve. It had lost none of its resilience. Its surface was slippery, apparently from serous fluid.

Removal of the sleeve bared the surface of the nerve junction. As early as five days post operative, the nerve ends were found reconnected by a cylindrical sheath which had grown along the inside of the sleeve. The interior was still highly fluid. At five and seven weeks post operative, the connection was firm. Except for its greater transparency, the level of the former gap could not be distinguished. The nerve in this region offered the aspect of a continuous cylinder (Fig. 1) with a perfectly smooth glossy surface without a trace of scar tissue or other unfavorable reaction against the metal.* The fact that the nerve can thus slide freely in the sleeve, constitutes one feature in which the tantalum cuff is superior to frozen-dried arteries, in which local adhesions of the nerve to the inner wall of the sleeve are not uncommon.

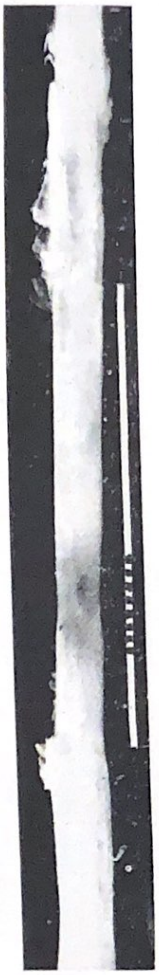

FIG. 1. Peroneal nerve of spider monkey, 5 weeks after sutureless reunion of the stumps (gap 4 mm.) with tantalum cuff. The cuff has been removed. Its former site is indicated by a white rule, the dotted part of which shows the extent of the original gap. Proximo-distal direction from top to bottom. ×3.

The microscopic picture bears out the macroscopic appearance of perfect reunion. Figure 2 illustrates the junction of a peroneal nerve as it appeared after the removal of the cuff without further trimming of the surface. One notes that no foreign body reaction or perineurial scar formation has occurred anywhere within the sleeve. For the rest, the picture speaks for itself. Specifically, the following points describe the character of the union.

(1) The gap has become bridged by a tissue which proceeded to form an integral link between the stumps, rather than merely a cementing scar.

(2) Sheath cell cords and nerve fibers have passed in straight parallel alignment through the gap into the distal stump and straight on down the latter.

(3) There is no profuse branching, straying and commingling of fibers at the level of the union.

* Concerning the indifference of tissues to tantalum, see Burke,[1] and Pudenz and Odom.[2]

(4) There has been no ingrowth into the junction of cicatricial connective tissue. All endoneurial and perineurial connective tissue has likewise been turned into a strictly longitudinal course, where it cannot impede nerve fiber growth.

(5) High liquid content of the tissue forming the junction has been preserved. This can be told directly from the loose texture of the tissue and also from its greater shrinkage during fixation, which gives it a "waistline" appearance. In spite of the abundance of liquid channels, the mechanical firmness of the link is assured by the tensile strength of the longitudinal strands of endoneurial fibers serving as ties.[7]

(6) No local edemas, neuromas or gliomas have formed.

(7) Since the nerve fibers, in passing from the proximal to the distal stump, maintain a steady straight course, they will restore a more orderly pattern of connections between the centers and the periphery than would otherwise be possible. This may have an important bearing on functional recovery.[6]

(8) Vascularization of the junction has been ample. The main vessels have grown straight through, following the general longitudinal di-

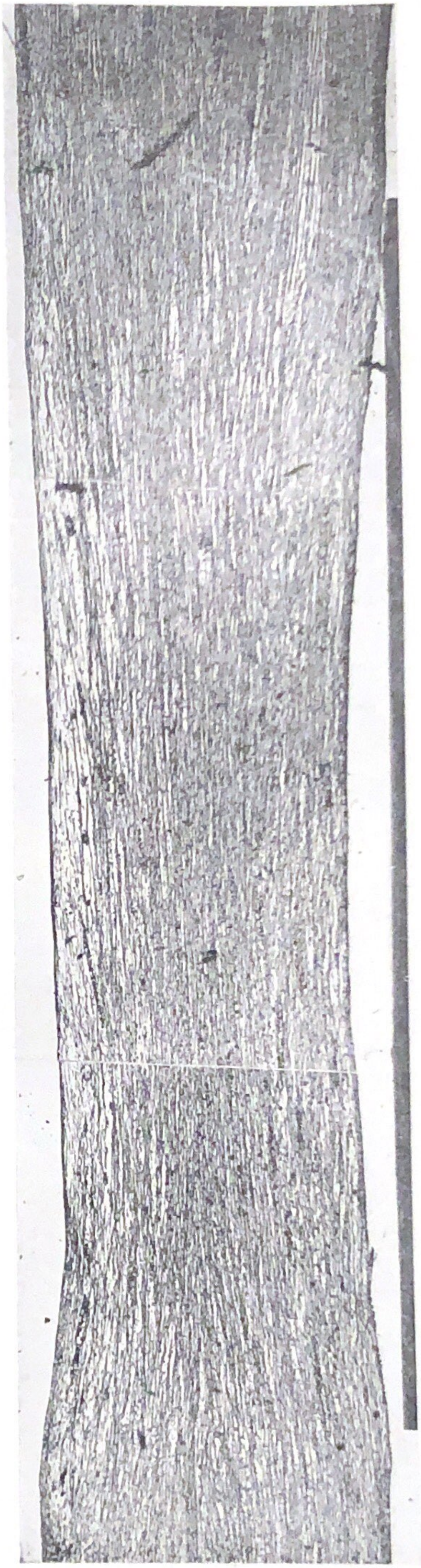

FIG. 2. Photomicrograph of a longitudinal section of the same nerve as in Figure 1. Silver impregnation after Bodian. The extent of the original gap between the stumps is indicated by the black rule on the margin. Note that the old perineurium of the stumps ends at the levels of the original cut surfaces, thus marking the limits of the former gap. Proximo-distal direction from top to bottom. ×43.

rection, and have supplied the whole region with a network of capillaries. In fact, this vascular supply from the intraneural sources is so abundant that it makes the recurrent warnings against the wrapping of suture lines, on the grounds that such procedures prevent extraneural vessels from penetrating, appear wholly unwarranted.

Rate of axon downgrowth has not yet been established. After 5 weeks, the peripheral stump was densely populated with regenerated axons at a level 20 mm. beyond the original cut surface. There is no record of just how much farther they had advanced, except that they had not yet reached the next distal sample level, 55 mm. from the cut. The whole picture, however, is such that the later outcome can be predicted on the basis of past experience with many hundreds of nerve unions studied both histologically and functionally. Unions such as the ones described here will lead to prompt and full reinnervation of the periphery, free from the impeding and delaying effects of intraneural fibrosis. In view of the predictability of the outcome, presentation of the results in this early phase has seemed justified. The functional results will be reported at a later date.

The two cases mentioned above, in which the sleeves had become buckled up, were total failures. Holes had formed at the dents and scar tissue had penetrated freely through these openings. The interior was filled with a bloody soft mass, evidently a residue of repeated hemorrhages. Except for a few strands along undamaged parts of the sleeve wall, there was no firm connection between the stumps. The proximal stump ended in a neuroma. The failure of effective reunion was so patent that no histological study was made. Creased and dented sleeves are obviously a potential source of injury and irritation to the nerve. However, no further mishaps of this kind have occurred since those early accidents. Yet, it is well to keep in mind that the danger of such an occurrence would increase in the vicinity of a joint, calling for protective measures such as temporary fixation.

The contrast between the successful and unsuccessful cases makes it clear that the question of the merit of using tantalum—or any other material, for that matter—in the repair of nerves, cannot be answered in a general way. Much depends on how the material is being used. If used properly, tantalum sleeves seem to perform very adequately as links between unsutured nerve stumps.

The obvious limitation, that they are applicable to straightway unions only and would be unsuitable where nerves are subject to bending, e.g., at a joint, might in some cases be overcome by leaving the sleeve in place only just long enough to permit firm reunion of the stumps and the formation of a new nerve sheath, while the joint is in fixation, and then reoperating for removal of the cuff, which can be easily pulled out in one piece, with a single move, without danger to the nerve or its circulation. But there will undoubtedly remain certain classes of lesions in which the use of rigid sleeves will be impracticable.

Aside from the excellent frame they provide for nerve regeneration, tantalum sleeves simplify the technique of nerve union considerably, and thus save time. Moreover, they can be easily applied to nerves of even the smallest caliber which would defy neat end-to-end suture.

SUMMARY

A method is described by which tantalum foil can be fashioned into resilient self-sealing tubes, which may be used as cuffs for the sutureless linking of severed nerve stumps in the manner previously described for arterial sleeves.

Preliminary observations on monkey and cat nerves joined by this method have demonstrated that excellent reunion between the stumps with the properties required for optimal nerve regeneration may be achieved if the sleeves have been suitably shaped and properly handled.

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