STRETCH INJURY OF PERIPHERAL NERVE
Acute Effects of Stretching on Rabbit Nerve

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Stretch injuries of peripheral nerves now occur frequently because of the increasing number of severe, violent accidents. Most injuries of the brachial plexus are of this kind (Horsley 1899, Jefferson 1930, Stevens 1934, Seddon 1948, Barnes 1949, Haftek 1966). Among the peripheral nerves, apart from the brachial plexus, the lateral popliteal nerve is most often exposed to stretch injury (Platt 1940, Hight and Holmes 1943).

The mechanism and pathology of stretch injury of a nerve remain rather poorly understood. There is general agreement that severe stretch produces a diffuse lesion, the extent of which is sometimes very difficult to determine (Seddon 1944). Within the lesion, which is often in continuity, there is a great variety of histological change. A common result is severe intraneural scarring, sometimes with complete absence of nerve elements, a consequence of the tearing of blood vessels, epineurium, perineurium and intrafunicular tissue (Hight and Holmes 1943, Hight and Sanders 1943, Blackwood and Holmes 1954, Bonney 1959). After such a lesion recovery is usually very poor.

Nevertheless, certain clinical and experimental observations show that nerve trunks are highly resistant to stretching. Mitchell (1872) reported a case in which the sciatic nerve of a patient was accidentally “pushed fully four or five inches out of its path, and very much elongated. Some pain resulted, but the sense of touch was scarcely disturbed.” He also showed that motor nerve conduction persisted in the sciatic nerve of a rabbit after it had been elongated 25 per cent. Good spontaneous recovery was observed after stretching the peroneal nerve of the cat up to twice its initial length (Denny-Brown and Doherty 1945). Furthermore, Leffert and Seddon (1965) observed good spontaneous recovery after closed injuries of the lower part of the brachial plexus, some of which were probably traction lesions.

It is not clear, however, what degree of stretching is likely to produce only neurapraxia or axonotmesis, and what will give rise to neurotmesis. These terms were introduced by Seddon (1943) to describe, in the order given: damage that is not followed by Wallerian degeneration; damage limited to axons and their myelin sheaths, which is followed by degeneration; and total disintegration of a nerve, not necessarily with loss of continuity. It is also uncertain whether nerve fibres break before rupture of the epineurium and perineurium occurs, as some authors believe (Blackwood and Holmes 1954, Sunderland and Bradley 1961a), and as some histological evidence would indicate (Liu, Benda and Lewey 1948).

A great deal of work has been performed on this subject. This has been summarised recently by Sunderland and Bradley (1961a, b, c), but the conclusions are not clear-cut. The purpose of the present study is to attempt to find answers to some of these questions.

MATERIAL AND METHODS

The tibial nerves of ten-week-old albino rabbits of both sexes were excised immediately after death, placed in holders and stretched by two methods: 1) Gradual stretching performed on the “Instron” universal testing machine at a constant rate and relatively slowly—0.5 millimetre per minute; the stress-strain relationships were recorded. 2) Instantaneous stretching applied to the nerves by dropping loads. During stretching the nerves were bathed in Ringer’s
solution at a temperature between 30 and 36 degrees Centigrade. Whole lengths of stretched nerves were then examined by light and electron microscopy (Siemens Elmiskop I A). For light microscopy, the nerves were fixed in Fleming's solution and stained by Kultschitsky's haematoxylin and van Gieson. For electron microscopy the nerves were fixed for three hours at 4 degrees Centigrade in 1 per cent osmium tetroxide in Ringer's solution buffered to pH 7.4 with veronal acetate. Some specimens were then immersed in 1 per cent phosphotungstic acid in absolute ethanol for three hours; others, after embedding in Araldite and sectioning with a Porter-Blum microtome, were stained on the grids with a 3 per cent solution of uranyl acetate and 1 per cent lead citrate. The time interval before fixation varied from ten minutes to two hours. Forty-nine nerves taken from twenty-six rabbits were tested.

![Figure 1](image-url)

**Fig. 1**

A typical graph made by the Instron machine during gradual stretching of the nerve up to complete rupture. The first part of the graph (a) is a curve which corresponds to extension of the epineurium and straightening of the funiculi. The second part (b) is a straight line; the stretched nerve obeys Hooke's law and behaves as an elastic material. At the limit of elasticity (interrupted arrow) the load decreases suddenly. Further elongation continues with a steadily diminishing load. There is then no proportionality between stress and strain (c). The nerve behaves as a viscous material. The graph declines slowly to zero and finally there is complete rupture of the nerve (interrupted arrow). Solid arrows show the points of elongation at which the nerves were examined histologically.

**RESULTS**

**GRADUAL STRETCHING**

When a nerve is stretched by the Instron machine a characteristic graph is obtained (Fig. 1). It is composed of three parts. The first (a) is a curve illustrating the stress-strain relationship during straightening of the nerve, the bundles of which are usually undulated. The second part (b) shows a linear relationship between stress and elongation (strain) of the nerve, which is characteristic of elastic material. Then the load decreases suddenly, when the "limit of elasticity" of the nerve trunk has been reached. Elongation continues with a steadily diminishing load. The third part (c) of the graph, beyond the limit of elasticity, declines slowly to zero and represents the stress-strain relationship characteristic of viscous material.

Before the experiment started even the very least stretching of the nerve was avoided. In the first period of stretching, the nerves were elongated by a load too small to be recorded. As soon as the "Instron" was able to record the smallest load the length of stretched nerve was measured. This was regarded as the initial length of nerve.

The results of these experiments will be considered in three groups. The first group consisted of six nerves stretched to a point just short of the limit of elasticity (Fig. 1). Three specimens of this group were stretched three, four and six times up to the same point. The nerves were elongated from 39.4 to 72 per cent, the mean value being 51.1 per cent.

Macroscopic observations—When elongation reached about 30 per cent of the initial length one point on the nerve became pale and a large blood vessel, which was usually seen on the
surface of the nerve, ruptured at this site. After relaxation the remaining elongation was 18.2 per cent mean value. Except for slight tortuosity and the rupture of the epineurial vessel, no other macroscopic changes could be detected.

**Histological findings**—All components of the nerve trunk were present throughout the stretched part. The epineurium, perineurium and endoneurium, as well as the Schwann basement membrane tubes, remained intact. The cross-sectional areas of the stressed funiculi and nerve fibres were markedly reduced. The normal undulation of nerve fibres was absent, the fibres being very straight and closely packed. The myelin of most of them was swollen, the lamellae being separated and disrupted. The axons were narrowed and many showed beading (Fig. 2). Some capillary blood vessels were compressed and the endoneurial spaces were reduced.

**The second group** consisted of seven nerves stretched up to the limit of elasticity (Fig. 1). The nerves were elongated from 41.7 to 90.5 per cent, the mean being 69.3 per cent.

**Fig. 2**

Longitudinal section through a nerve stretched to just short of the limit of elasticity; elongation 49.5 per cent. The middle funiculus is the most stressed; in it the nerve fibres run straight and are thinner than normal. The myelin of most of them is disorganised. Beading is seen in all nerve fibres. The endoneurial sheaths are in continuity. (Kultschitsky's haematoxylin-van Gieson.)

**Macroscopic observations**—At the point of maximal stress, which became pallid, the epineurium ruptured and retracted, so that the funiculi were seen. A sharp snapping sound was usually heard at the moment of rupture. After relaxation, elongation was reduced by an average of 26.4 per cent. However, the length of the part exposed by rupture of the epineurium remained almost unchanged.

**Histological findings**—The proximal part of the stretched nerve was composed of two parts. One was the branches to the calf muscles, which were cut during dissection of the nerve; this part of the nerve was not stretched and appeared to be normal. The other part, the stretched tibial nerve, contained all components of the nerve. The connective tissue sheaths were intact but there were narrowing of the endoneurial spaces, diminution of the diameter.
FIG. 3
Transverse section through the proximal part of a nerve stretched up to the limit of elasticity; elongation 80 per cent. A partly ruptured epineurium and almost intact perineurium are seen. The intrafunicular tissue is compressed, but the endoneurial sheaths are intact. (Kultschitsky's haematoxylin-van Gieson.)

FIG. 4
Transverse section through the middle part of a nerve stretched to the limit of elasticity: elongation 80 per cent. Funiculi with largely intact perineurium but completely ruptured epineurium are seen. The endoneurial sheaths are intact. (Kultschitsky's haematoxylin-van Gieson.)
of the fibres and breaks in the myelin sheaths. As the site of rupture of the epineurium was approached, shreds of epineurium were found but the perineurium and endoneurium were in continuity (Fig. 3).

**Fig. 5**

Longitudinal section of a nerve stretched to the limit of elasticity: elongation 55.9 per cent. The epineurium is ruptured. Perineurium and endoneurial sheaths are in continuity. The nerve fibres are straightened, the myelin of most of them being disorganised. (Kultschitsky's haematoxylin-van Gieson.)

**Fig. 6**

Transverse section through the distal part of a nerve stretched up to the limit of elasticity: elongation 80 per cent. All connective tissue sheaths are intact. Intrafunicular tissue is compressed. (Kultschitsky's haematoxylin-van Gieson.)

Some millimetres farther, naked funiculi were found with the perineurium usually intact (Fig. 4). Although the endoneurial sheaths were still in continuity the myelin in most fibres was damaged (Fig. 5). Towards the distal part of the nerve, funiculi were again observed with
partial rupture of the epineurium (Fig. 3). Within the distal part all elements of the nerve trunk were found, the funiculi being stressed in the same manner as within the proximal part (Fig. 6).

The third group consisted of eleven nerves stretched gradually until they ruptured. The nerves were elongated from 53.3 per cent to 122 per cent, the mean being 73.3 per cent. The mean elongation at the point of limit of elasticity for these nerves was 55.7 per cent. Hence, after rupture of the epineurium occurred, the nerves were further elongated by 17.6 per cent of their initial lengths.

Macroscopic observations — When a nerve was elongated beyond the limit of elasticity, only the part deprived of epineurium was affected and it became progressively thinner. When the nerve became very thin and was about to break, relaxation did not result in any noticeable shortening. Further elongation led to complete rupture of the nerve at the thinnest part, which consisted of a fine strand of tissue composed of a single funiculus. The manner of breaking was similar to that of a slowly elongating molten glass fibre.

Histological findings — The outer zone of both stumps contained all elements of the nerve trunk and resembled exactly the corresponding parts of the nerves stretched to the limit of elasticity (Fig. 6). In some specimens, usually within the peripheral stump, lacunae were found, the perineurial tubes being devoid of nerve fibres and endoneurium. Some of them contained a small amount of funicular tissue (Fig. 7). In the middle part of the stumps naked funiculi with ruptured epineurium were found (Fig. 3), and a little farther towards the point of rupture naked funiculi only were present (Fig. 4). Endoneurial sheaths and basement membranes were intact, the endoneurial spaces being much reduced. Myelin was swollen and disorganised. The axons were narrowed and of irregular shape (Fig. 8). Still closer to the point of rupture...
Electron micrograph of a nerve ruptured after being gradually stretched; elongation 85.7 per cent. Transverse section through the middle part of the peripheral stump. It shows nerve fibres with disorganised myelin (my) and narrowed distorted axons (ax) containing vacuoles. Basement membranes (bm) and endoneurium (en) are intact. Endoneurial spaces are extremely reduced. (Phosphotungstic acid stain.)

Fig. 8

Electron micrograph of the same nerve as in Figure 8. Transverse section near the tip of the peripheral stump. Nerve fibres are still in continuity. Basement membranes (bm) are intact, but some disorganisation of endoneurial collagen (en) is seen. The myelin (my) is disintegrated and the axons (ax) are very thin. (Phosphotungstic acid stain.)

Fig. 9

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were some completely destroyed funiculi with ruptured perineurium, others still possessing intact perineurial sheaths. Where the perineurium had ruptured there were still nerve fibres in continuity. Basement membranes were intact, although some disorientation of endoneurial collagen fibrils was seen. The myelin of all fibres was disorganised and the axons were very thin, presumably both compressed and elongated (Fig. 9). The tips of the stumps consisted of a small amount of intrafunicular tissue—that is, endoneurium and nerve fibres. The endoneurial collagen was highly disorientated. Some nerve fibres were completely disintegrated whereas others still possessed their basement membranes (Fig. 10).

**INSTANT STRETCHING BY DROPPING LOADS**

In this series, loads of 300 grammes (fifteen experiments), 1,814 grammes (six experiments) and 4,536 grammes (two experiments) were dropped through a distance of 20 millimetres. The results will be presented in two groups. **The first group** consisted of six unruptured nerves stretched by 300 grammes. **Macroscopic observations**—The differences in length before and after stretching varied from 1 to 3 millimetres, with a mean value of 1·2 millimetres. After stretching the nerves displayed a greater or lesser degree of tortuosity. **Histological findings**—These were similar to those of gradual stretching without breaking (see above). The connective tissue sheaths remained intact. The endoneurial spaces were reduced, and the fibres had lost their normal undulation (Fig. 2). **The second group** consisted of seventeen nerves which were ruptured with loads of 300, 1,814 and 4,536 grammes. All these nerves showed similar changes and therefore will be considered together. **Macroscopic observations**—When the load of 300 grammes was applied the amount of energy was just enough to rupture the nerve. The fall of the load was therefore momentarily arrested,

**Fig. 10**
Electron micrograph of the same nerve as in Figure 9. Transverse section through the tip of the peripheral stump. It shows ruptured nerve fibres devoid of endoneurial sheaths and basement membranes. The endoneurial collagen is disorientated. Other nerve fibres are still surrounded by basement membranes (bm). Part of a Schwann cell nucleus (n) is also present. (Phosphotungstic acid stain.)
but continued when the nerve ruptured. When greater loads were applied, the nerves were ruptured immediately. The tips of the stumps were usually conical and greatly elongated if the load was small.

**Histological findings**—In the outer parts of both stumps the connective tissue sheaths were intact. Funicular tissue was compressed, the spaces between the nerve fibres being markedly reduced. Myelin was usually broken, the changes being more pronounced within some funiculi than in others. Generally, the picture was again very similar to that shown in Figure 6. As the point of rupture was approached, extremely stressed funiculi were seen, but the nerve trunk still possessed all its essential components (Fig. 8). The tips of the stumps consisted of pieces of naked intrafunicular tissue with disorientated endoneurial collagen fibrils and destroyed nerve fibres (Fig. 10). Usually the naked part of the nerve was much shorter than in the nerves that were gradually ruptured. Sometimes ruptured epineurium, perineurium and intrafunicular tissue were all found at the tip of a stump.

**DISCUSSION**

Peripheral nerves are not homogeneous structures. The connective tissue sheaths are more robust (Thomas 1963, Gamble and Eames 1964), whereas myelin and axoplasm behave as fluids (Young 1945). All biological tissues are in various ways visco-elastic materials (Abrahams 1965), some possessing more elastic components, others being more viscous. It is impossible to separate individual components of a peripheral nerve and examine their particular properties. However, the evidence from the present experiments suggests that nerve trunks possess a high degree of elasticity. Stretched nerves with unruptured epineurium were able to recover 71.8 per cent of their initial lengths after gradual stretching, and 96.9 per cent after instant stretching. The first part of the curve in Figure 1 shows that there is no proportion between stress and strain. The second part of the graph shows a linear relationship between stress and strain, the stress being proportional to strain. Hooke's law applies and the nerve behaves as an elastic material. Beyond the limit of elasticity, which corresponds to rupture of the epineurium, there is no longer proportion between stress and strain. Further elongation continues with diminishing loads, as is shown by the third part of the graph, which represents the elongation of the funicular tissue and in some specimens its sliding out of the perineurial tubes. This part of the graph indicates that intrafunicular tissue behaves mainly as a viscous material. It explains why, after rupture of the epineurium, nerve trunks are able to recover only 26.4 per cent of their elongation, and at the point just before rupture would occur they are not able to shorten by any measurable amount.

The tortuosity of stretched nerve trunks, which was also observed by Tarlov and Day (1954) within nerve roots, indicates that the ability of a nerve trunk to recover after a strain is mainly because of the elastic properties of the epineurium whilst the funiculi remain elongated.

All these findings suggest that the elasticity of the whole nerve trunk depends mainly upon the epineurium, much less on the perineurium and only a little on the intrafunicular tissue. Some elasticity is possessed by endoneurium (Schneider 1952, Lubinska 1952), the basement membranes of Schwann cells (Haftek and Thomas 1968) and perhaps also axons (de Rényi 1929), which, however, is too small to protect them against forces acting during a stretch injury. Thus it is the epineurium that protects the fine structures of a peripheral nerve during stretching.

The trunk of a peripheral nerve is a very strong structure: loads ranging from 18 to 165 kilograms for the sciatic nerve and 20 to 50 kilograms for the median and ulnar nerves are necessary to rupture them (Sunderland and Bradley 1961a). The elongation to the point where damage of the nerve occurs varied markedly. Hight and Sanders (1943) gave a value of 11 per cent in dogs; Denny-Brown and Doherty (1945) reported 100 per cent in cats; Liu et al. (1948) gave 6 per cent for human cadaver nerves; Hoen and Brackett (1956), 25 to 50 per cent
in dogs; and Sunderland and Bradley (1961a) 20 to 32 per cent in human cadaver nerves. In these experiments the mean elongation at the limit of elasticity was 69·3 per cent, and at the point of rupture 73·3 per cent.

When the nerve trunk is stretched gradually, the initial elongation is of the epineurium with straightening of the funiculi, which normally lie lax within the epineurial collagen (Key and Retzius 1876, Schneider 1952). The nerve fibres, which also are normally undulated, become straight. Further elongation, up to the limit of elasticity, involves all components of the nerve, but the main resistance against stress is borne by the epineurium and perineurium.

The breaking of myelin sheaths and compression of axons at this stage of stretching is due mainly to the pressure by the elongated perineurium, the calibre of the tube being greatly reduced. Elongation of the nerve fibres is another factor contributing to these changes. At the limit of elasticity the epineurium ruptures but the funiculi continue to elongate. This further elongation is brought about by a much smaller load, only 14·8 per cent of the maximum load, measured just before the limit of elasticity is reached. Next, some perineurial sheaths rupture and then, after further elongation, complete division of the nerve fibres within the funiculi takes place. Finally the whole nerve ruptures. On no single occasion did the endoneurial sheaths or nerve fibres give way before the epineurium and the perineurium. Similarly, the perineurium was never seen to be ruptured within the intact epineurium. On the other hand, the tips of the ruptured nerves consist of intrafunicular tissue, completely deprived of perineurium and epineurium.

When instantaneous stretching is applied, the perineurium and then the intrafunicular tissue rupture after the epineurium. There is no essential difference in the pattern of damage after gradual and after sudden stretching. This accords with the observations of Hight and Sanders (1943). Usually the naked part of the nerve, that is the funicular tissue at the tips of the stumps, is much shorter after sudden rupture, although there is a greater variety in the changes so produced. The epineurium and perineurium may be ruptured longitudinally, obliquely or transversely and the normal orientation of endoneurial collagen and nerve fibres may be lost.

The longitudinal extent of the damage to a ruptured nerve is always great and varies from 3 to 5 centimetres. Changes in nerve fibres resulting from compression and elongation are seen throughout its length.

The damage to the nerve caused by stretching up to the limit of elasticity would correspond to neurapraxia or axonotmesis. Beyond the limit of elasticity, neurotmesis, either of individual funiculi or the whole nerve trunk, is the essential damage.

This pattern of stretch injury differs from that described in some earlier communications. Liu et al. (1948) found that all nerve fibres "were completely interrupted within their perineurial tubes when the nerve was stretched beyond 10 per cent", although "the perineurium withstood overstretching in all experiments". Sunderland and Bradley (1961a) described the pattern of break of a nerve as follows: "Load is first resisted by the perineurium which protects the contained undulating nerve fibres of the funiculus. With increasing elongation the nerve fibres are straightened and then stretched along with the perineurium. As the load increased, rupture of some nerve fibres occurred within bundles, while others continued to elongate. Finally some bundles ruptured, often at widely spaced intervals along the nerve. This occurred without, however, necessarily precipitating failure of the entire trunk; the surviving bundles continued to withstand the increasing load. Finally, funicular breakdown involved a sufficient number of bundles to cause failure of the entire nerve. All bundles had then ruptured and the nerve elongated rapidly as a plastic structure."

These opinions were presumably based on the finding, within a given piece of nerve, of torn intrafunicular tissue with continuity of perineurium and epineurium. But correct interpretation is possible only if these appearances are related to those throughout the whole length of the stretched nerve. "Empty spaces" within an intact perineurial tube were also
found in our experiments, but such breaks within the perineurium occurred only after rupture of the epineurium and perineurium elsewhere. Empty spaces were sometimes found several centimetres away from the point of breakage of the epineurium. This is in agreement with the statement of Blackwood and Holmes (1954) that "at the point of greatest damage the tear may involve nerve fibres, endoneurium and perineurium, while, at points far above and below it, the perineurium may be intact, but within it nerve fibres and endoneurial tubes may be torn". Hight and Sanders (1943) found "rupture of Schwann tubes in the regions where stretching is most severe". This conclusion was supported by photomicrographs of longitudinal sections of the "most distal part of the peripheral stump of stretched nerve", showing a small funiculus with ruptured Schwann tubes. But they also said that the most distal part of the peripheral stump "was the region where the nerve was stretched to the limit of its extensibility".

SUMMARY

1. Forty-seven tibial nerves of rabbits were stretched, twenty-four gradually by the Instron machine and twenty-three suddenly by dropping a load. The stretched nerves were examined histologically throughout their length.
2. Nerve trunks possess a high degree of elasticity, which is mainly a feature of the epineurium.
3. The initial elongation of the nerve is due to extension of the epineurium and straightening of the funiculi and of the nerve fibres. Such elongation is "physiological" in the sense that it does not affect the nerve fibres.
4. The first structure to be ruptured during stretching is the epineurium; this occurs when the nerve trunk has reached its limit of elasticity.
5. Before rupture of the epineurium the damage to the nerve fibres is either neurapraxia or axonotmesis, because the endoneurial sheaths and Schwann tubes remain intact.
6. Beyond the limit of elasticity very severe damage of the nerve trunk occurs; all elements of the nerve may be ruptured. If less violent force is applied, some funiculi may survive. The longitudinal extent of the lesion is always great, reaching 2 to 5 centimetres in the rabbit.

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