

Stretching of the brachial plexus in rabbits

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The brachial plexus of rabbits was stretched until mechanical failure. The level and site of rupture varied according to the direction of the stretching force. Upward and lateral traction of the forelimbs caused spinal nerve-root avulsions combined with nerve-trunk ruptures distal to the dorsal root ganglions. In such tractions the C5 nerves consistently exhibited postganglionic nerve-trunk rupture. The C6, C7, and C8 nerves had root avulsions. The T1 nerve was avulsed from the spinal cord in 7 cases out of 10; the other 3 cases had postganglionic nerve-trunk rupture. Downward traction of the forelimbs caused nerve avulsions from the scapulohumeral muscles innervated by the terminal branches of the brachial plexus and peripheral nerve ruptures in the course of the arm. The force producing trunk rupture of the C6 nerve was twice as great as that for root avulsion. The required strain was similar for nerve trunk rupture and root avulsion.

The mechanisms of root avulsion following traction injury of the brachial plexus are not clear. We have assessed traction forces in different directions causing rupture of the brachial plexus in rabbits.

Materials and methods

Nineteen white (2.0-2.7 kg) rabbits were killed with 100 mg/kg i.v. pentobarbital. The right brachial plexus was explored by osteotomy of the clavicle and by cutting the subclavian vessels and the muscular insertions to the scapula and the humerus so that the right forelimb was connected to the neck only by the brachial plexus. A Kirschner wire was drilled through the olecranon. An additional wire was inserted in the contralateral tibial tuberosity, the contralateral olecranon, or the ipsilateral mandible. Each of the latter three was used to provide counteraction for nerve stretching. Upward traction between the elbow and contralateral hindlimb and lateral traction between the elbow and contralateral elbow

were performed on 5 rabbits each. Downward traction between the elbow and ipsilateral mandible was performed on 3 rabbits. The forelimb was hanging down through simple gravity when the nerve stretching started. The hindlimb was immobilized and suspended with a bandage from the upper transverse axis of the loading apparatus when the lateral traction was applied. The elbow was then vertically stretched until mechanical failure of the brachial plexus. The inserted Kirschner wire was connected by a wire, 0.8 mm in diameter, to the axial-loading apparatus equipped with a graphic recorder (Shimadzu Autograph S-500-C). The brachial plexus was elongated at a constant rate of 500 mm/min. During stretching the nerves were immersed in a saline solution to prevent desiccation. To monitor separately root avulsion and nerve-trunk rupture, the C6 nerve was tested after cutting the other spinal nerves of the brachial plexus; it was difficult to consistently produce root avulsion or nerve-trunk rupture in the spinal nerves except in the C6 nerve. The traction force on the C6 nerve was applied in two directions, i.e., between the elbow and mandible and between the elbow and contralateral elbow. Each mode of traction was performed on 3 rabbits. The cross-sectional area of the C6 nerve on the contralateral healthy side was measured with a digitized planimeter, using a 10x-enlarged photograph of the cut surface of the nerve. The progress of elongation was re-

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Table 1. Injury pattern of the spinal nerves during stretching of the brachial plexus

	Stretching of elbow vs. hindlimb (n 5) /contralateral elbow (n 5)	
	Nerve-trunk ruptures	Root avulsions
C5	5/5	0/0
C6	0/0	5/5
C7	0/0	5/5
C8	0/0	5/5
T1	1/2	4/3

Table 2. Mean load corresponding to the breakdown of each spinal nerve during stretching of elbow vs. hindlimb and elbow vs. contralateral elbow

	Load (range) newtons	
	Elbow vs. hindlimb (n 5)	Elbow vs. contralateral elbow (n 5)
C5	8 (3-11)	9 (5-13)
C6	18 (14-22)	15 (13-17)
C7	19 (14-23)	15 (12-20)
C8	20 (16-23)	23 (19-31)
T1	19 (10-31)	19 (17-22)

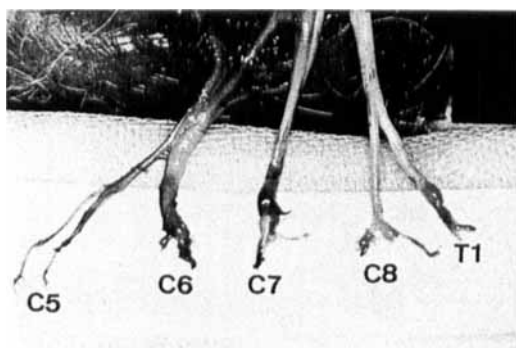


Figure 1. The brachial plexus was stretched and torn off when the elbow was pulled out of the hindlimb. The C5 nerve showed postganglionic nerve rupture, and the C6, C7, C8, and T1 nerves were avulsed from the spinal cord.

corded with a video camera to enable us to place a methylene blue dye mark 20 mm along the course from the C6 nerve to the more peripheral brachial plexus.

Anatomy of the brachial plexus. The brachial plexus of the rabbit comprises five spinal nerves: C5-C8 and T1. The C5 nerve has the supraclavicular nerve as one branch and a small branch to the C6 nerve. The C6 nerve has a branch to the C7 nerve and also gives branches to the suprascapular and the subscapular nerves. The C7, C8, and T1 nerves compose the middle and lower portions of the brachial plexus to terminate in the axillary, radial, median, and ulnar nerves. The musculocutaneous nerve branches from the course of a median nerve. In 10 cases, the diameter of each nerve was measured with vernier calipers. The largest spinal nerve was the C7 nerve (mean diam. 1.4 mm) in 6 cases and the C8 nerve (mean diam. 1.3 mm) in 4 cases. The C5 nerve was the smallest (mean diam. 0.8 mm) in all the cases.

Results

The site and level of nerve injuries of the brachial plexus varied according to the direction of the traction force. Root avulsions and peripheral nerve-trunk ruptures were found when traction was employed in two modes of directions, i.e., between the elbow and hindlimb (upward traction of forelimb; Figures 1 and 2) and between the elbow and contralateral elbow (lateral traction of forelimb; Figure 3). In these two modes of stretching of the brachial plexus, the T1 nerve was injured first, followed by, successively, the C8, C7, C6, and C5 nerves. All C5 nerves were injured postganglionically. The T1 nerves had root avulsions in seven, and postganglionic nerve-trunk ruptures in three nerves out of 10. All C6, C7, and C8 nerves had root avulsions (Table 1). When the elbow was pulled away from the hindlimb, the load at failure was, on an average, 20 N. The corresponding load averaged 23 N when the elbow was given a strong pull against the contralateral elbow (Table 2). When the elbow was pulled away from the mandible (downward traction of forelimb; Figure 4), all the nerves were avulsed from the scapulohumeral muscles innervated by terminal nerves of the brachial plexus, and the peripheral nerves were ruptured in the course of the arm. The rupture of the brachial plexus in these cases occurred at a load of 38 (36-39) N. This value was thus much higher than that for lateral or upward stretching of the forelimb. Nerve-trunk rupture distal to the dorsal-root ganglion of the isolated C6 nerve occurred when the elbow was tugged downward. The stress value for the load at the breaking point was 46 (44-49) MPa, and the strain was 7 percent. Finally, the C6 nerve was avulsed from the spinal cord when the elbow was pulled laterally. At the moment of root avulsion, the stress value was 26 (23-27) MPa and the strain 9 percent. The stress for nerve-trunk rupture was about two times higher than

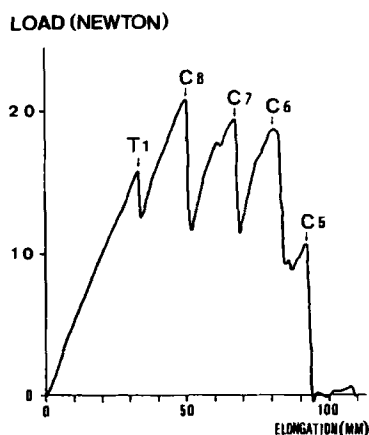


Figure 2. Load-elongation curve for stretching of the brachial plexus when the elbow was pulled apart from the hindlimb. T1-C6 sustained root avulsion and C5 postganglionic nerve rupture.

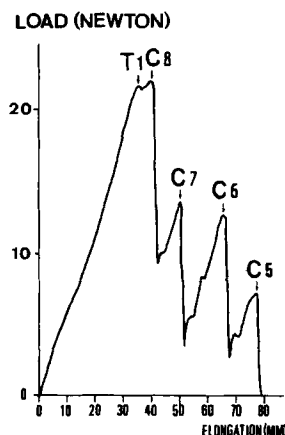


Figure 3. Load-elongation curve for stretching of the brachial plexus when the elbow was pulled against the contralateral elbow. T1-C6 sustained root avulsion and C5 postganglionic nerve rupture.

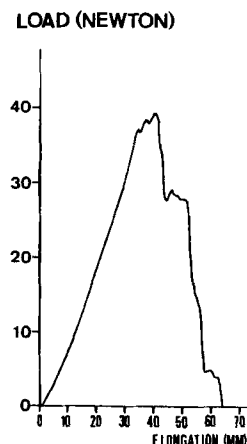


Figure 4. Load-elongation curve for stretching of the brachial plexus when the elbow was pulled against the mandible. The terminal branches of the brachial plexus were avulsed from the scapulohumeral muscles, and median and ulnar nerves were ruptured at the level of the arm.

that for root avulsion ($P < 0.01$). Similar strain values were obtained for both nerve-trunk rupture and root avulsion ($P > 0.05$).

Discussion

Severe traction injury of the brachial plexus frequently causes root avulsions combined with postganglionic nerve trunk ruptures. However, the site, level, and extent of nerve injuries vary. Some common factors have been found in the distribution of the lesions of the brachial plexus, i.e., postganglionic nerve rupture is common in the C5 nerve and root avulsions are most common in the C7 and C8 nerves followed by the C6 and T1 nerves (Kawai et al. 1988).

Which factors determine nerve-trunk ruptures and root avulsions? In this experiment the direction of the traction force proved to be a determinantal factor. Downward stretching of the forelimb caused nerve ruptures at the scapulohumeral muscle inlets of the terminal branches of the brachial plexus and the peripheral nerves. Upward and lateral tractions of the forelimb caused mostly root avulsions of the spinal nerves, especially the C6-C8 nerves. The C5 nerve always displayed peripheral nerve-trunk rupture, which is considered to be relat-

ed to a structural property of the nerve. The C5 nerve has always a large branch, the supraclavicular nerve, which does not form part of the brachial plexus. Because of this branching, the C5 nerve ruptures at the nerve branching to the C6 nerve. The T1 nerve exhibited either root avulsion or nerve-trunk rupture. One explanation is that the T1 nerve runs in the curve under the first rib, so that it is avulsed from the spinal cord or sometimes ruptures postganglionically according to the direction of load.

Sunderland and Bradley (1961) stressed that the perineurium was the structure most resistant to overstretching. However, Haftek (1970) suggested that the elasticity of the whole nerve trunk depended mainly upon the epineurium. In any case, nerve sheaths, the epineurium, and epineurium, possess more elastic components than the endoneurium and nerve fibers. Lundborg and Rydevik (1973) indicated that a complete standstill in all the intraneural vessels became evident at an 11 to 18 percent elongation (mean 15 percent) in the tibial nerves of rabbits. Various values have been reported for elongation causing nerve ruptures. Hight and Sanders (1943) gave a value of 11 percent for dogs; Denny-Brown and Doherty (1945) 100 percent for cats; Liu et al. (1948) 6 percent for human cadaver nerves; Hoen and Brackett (1956) 25-50 percent for dogs; Sunderland and Bradley (1961) 20-32 percent for human cadaver nerves; and Haftek reported 69 percent at the limit of elasticity and 73 percent at the

point of rupture in rabbits. This great disagreement is probably due to methodologic differences in measuring elongation and in species differences.

In our series the elongation of the breaking point of the nerve trunk was 7 percent. One reason for this lower value is that the stretching started when the forelimb was hanging down through simple gravity, the nerves being slightly stretched. Sunderland and Bradley (1961) indicated that under tension nerve roots fail 15 percent beyond the elastic limit and 25 percent at the mechanical rupture and that these val-

ues were lower than those for nerve trunks. The strength was also found to be much less than that for peripheral nerve trunk ruptures. This experiment did not show any substantial difference in strain values between root avulsion and nerve-trunk rupture. However, the stress values were two times higher for nerve-trunk rupture than for root avulsion. This can be explained by the fact that the nerve root lacks a perineurium and that the attachments of the nerve to the vertebral process are weaker than the force causing breakdown of the peripheral nerve trunk.

References

- Denny-Brown D, Doherty M M. Effects of transient stretching of peripheral nerve. *Arch Neurol Psych* 1945; 54:116-129.
- Haftck J. Stretch injury of peripheral nerve. Acute effects of stretching on rabbit nerve. *J Bone Joint Surg (Br)* 1970;52(2):354-65.
- Higget W B, Sanders F K. The effects of stretching nerves after suture. *Br J Surg* 1943;30:355-369.
- Hoen T I, Brackett C E. Peripheral nerve lengthening. I. Experimental. *J Neurosurg* 1956;13:43-62.
- Kawai H, Kawabata H, Masada K, Ono K, Yamamoto K, Tsuyuguchi Y, Tada K. Nerve repairs for traumatic brachial plexus palsy with root avulsion. *Clin Orthop* 1988;(237):75-86.
- Liu C T, Benda C E, Lewey F H. Tensile strength of human nerves. *Arch Neurol Psych* 1948;59:322-336.
- Lundborg G, Rydevik B. Effects of stretching the tibial nerve of the rabbit. A preliminary study of the intraneural circulation and the barrier function of the perineurium. *J Bone Joint Surg (Br)* 1973;55(2): 390-401.
- Sunderland S, Bradley K C. Stress strain phenomena in human peripheral nerve trunks. *Brain* 1961;84:102-119.
- Sunderland S, Bradley K C. Stress strain phenomena in human spinal nerve roots. *Brain* 1961;84:120-124.