

# Origin and composition of the brachial plexus in the alpaca (*Vicugna pacos*)

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**Abstract:** Alpacas (*Vicugna pacos*), members of the family Camelidae, are gaining popularity in Europe and world-wide. This study describes the origin and composition of the brachial plexus in alpacas and compares them with those of selected mammals. Six alpacas, aged one day to 16 years, were examined. In five animals, the plexus was formed by the ventral branches of C7, C8, and T1; in one specimen, T2 also contributed. After passing through the scalenus muscles – with C7 traversing separately from the caudal roots (C8, T1) – the roots continued as trunks toward the forelimb. Fibre exchange resulted in the formation of two cords. Nerves to the shoulder girdle muscles, except for the caudal pectoral nerve, contained only C8 fibre bundles. The suprascapular, subscapular, and axillary nerves arose from the cranial cord (C7, C8), which continued distally as the radial nerve (C8, T1). The caudal cord first gave rise to the cranial pectoral nerve (C8), followed by the caudal pectoral nerve (C8, T1) and the ulnar nerve (C8, T1), and then continued as the median nerve. The musculocutaneous nerve (C7, C8) originated at the trunk level, coursed caudally, and joined the median nerve in the ansa axillaris, resulting in the median nerve containing fibre bundles from all three spinal nerves. The reduced number of contributing spinal nerves and the distinctive arrangement of the plexus may be related to the elongated cervical vertebrae of alpacas. These findings support clinical applications, particularly in forelimb surgery and nerve block techniques, and provide comparative insights into morphological adaptation of the brachial plexus among mammals.

**Keywords:** cervical vertebrae; comparative anatomy; peripheral nerves; regional anaesthesia

Over the past few decades, the population of South American camelids has increased substantially outside their native range. In Germany alone, approximately 15 000 animals, predominantly alpacas and llamas, were reported in 2018 (Gauly 2019). Most husbandries today are small-scale, hobby-oriented farms keeping between one and 15 alpacas, and their popularity has risen markedly in the past two

decades (Wagner et al. 2022). With this trend, the demand for veterinary care has also increased, and alpacas are expected to require a comparatively greater therapeutic effort than traditional livestock species (Newman and Anderson 2009). Adequate clinical management, however, depends on fundamental knowledge of topographic anatomy, which remains scarce in this species. Existing anatomical

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studies are limited, mostly originating from South America (Goshima Watanabe 1976; Kitsutani Ogata 1978), or focusing on llamas (Arzone et al. 2013) or Old-World camelids (Smuts and Bezuidenhout 1987a). Consequently, veterinarians often rely on anatomical data from other domestic animals.

Alpacas display several external anatomical peculiarities, most notably their unusually long necks compared with those of most other mammals (Waringo 2018; Muller et al. 2021). This elongation is primarily due to the extended morphology of cervical vertebrae 3–6 (Arnold et al. 2017). Such features raise the question of whether the brachial plexus of alpacas arises like that in domestic mammals with shorter necks.

In mammals, the brachial plexus is formed by the ventral branches of several spinal nerves, which reorganise into a complex network before giving rise to the peripheral nerves of the thoracic limb (Miller 1934; Johnson et al. 2010). In the present study, the organisational terminology of roots, trunks, divisions, and cords is adopted, following conventions primarily established in human anatomy. These terms correspond to *radices*, *trunci*, *divisiones*, and *fasciculi*, respectively, and are not part of the official Nomina Anatomica Veterinaria (International Committee on Veterinary Gross Anatomical Nomenclature 2017), which recognises only the roots and trunks.

After emerging from the intervertebral foramina and passing between the scalene muscles, the roots of the plexus reorganise into trunks. Each trunk subsequently divides into anterior and posterior divisions (also referred to as cranial and caudal divisions), which further recombine to form cords. From these cords, the majority of the peripheral nerves of the brachial plexus originate. It should be noted that the term “root” in this study refers to the ventral branches of a spinal nerve contributing to the brachial plexus and not to the root of the

spinal nerve itself. The abbreviations C2–C8 and T1–T3 refer to the respective spinal nerves unless stated otherwise.

In most mammals, the brachial plexus is typically formed by the ventral branches of five spinal nerves. In dogs, ruminants, and horses, these are the ventral branches of C6, C7, C8, and T1–T2. In pigs, however, C5 rather than T2 contributes, yielding a composition similar to that of humans. Only in cats is the plexus composed of four spinal nerves (C6–C8 and T1) (Seiferle and Boehme 2003; de Lahunta and Evans 2013). Given the considerable distance between the forelimb and the fifth and sixth cervical vertebrae in alpacas, it remains unclear whether the plexus exhibits a caudal shift in its root origin, or whether the long neck does not affect its organisation.

The present study aimed to describe the root origin and composition of the brachial plexus in alpacas and to compare these findings with those reported in selected domestic and wild mammals. By addressing this knowledge gap, the study aims to advance understanding of morphological diversity within the mammalian brachial plexus and to provide veterinarians with a foundation for accurate diagnosis and treatment. In particular, knowledge of the origin, course, and target regions of nerves in the thoracic limb may improve clinical management of forelimb diseases and expand the application of local anaesthetic techniques in this region.

## MATERIAL AND METHODS

### Animals

Six Huacaya-type alpacas (*Vicugna pacos*; four males and two females) aged between one day and 16 years were examined (Table 1).

Table 1. Overview of the examined alpaca specimens including breed, sex, age, and number of dissected forelimbs

| Number | Type    | Sex            | Age       | Limbs |
|--------|---------|----------------|-----------|-------|
| 1      | Huacaya | castrated male | 16 years  | 1     |
| 2      | Huacaya | castrated male | 4 years   | 1     |
| 3      | Huacaya | female         | 1 day     | 1     |
| 4      | Huacaya | female         | 13 years  | 2     |
| 5      | Huacaya | male           | 0.5 years | 2     |
| 6      | Huacaya | castrated male | 13 years  | 2     |

All animals had either been euthanised for medical reasons unrelated to the nervous system or forelimb or had died of natural causes. No animal was euthanised specifically for this study.

We obtained the animals from various veterinary clinics and veterinarians following euthanasia. Carcasses were collected immediately after death and transported to the Department of Anatomy, Histology, and Embryology at the Faculty of Veterinary Medicine, LMU Munich. Thoracic and abdominal organs were removed, and the specimens were stored at  $-18^{\circ}\text{C}$  until dissection.

## Preparation

After complete thawing, the specimens were trimmed to the appropriate size. The examined material comprised the caudal cervical region and the thorax, or in large adults, only the cranial part of the thorax. Skin and fleece were removed, and the muscles of the limb, shoulder girdle, back, neck, and thorax were identified.

To allow medial access to the brachial plexus, the dorsal and caudal shoulder girdle muscles were detached, namely the *musculus latissimus dorsi* (*m. latissimus dorsi*), *m. trapezius*, *m. rhomboides*, and *m. serratus ventralis thoracis*. In some cases, the *m. pectoralis profundus* was separated from the sternum.

This approach exposed the medial aspect of the forelimb with most plexus nerves, as well as the lateral thoracic region, back muscles, and the passage of the brachial plexus toward the limb. After removal of the scalene muscles, the brachial plexus was dissected carefully proximally to the intervertebral foramina, with surrounding musculature removed only as necessary. In some cases, the proximal third of the first two to three ribs was also excised.

For further exposure, the lateral parts of the vertebral arches, including the transverse processes of the last cervical and first thoracic vertebrae, were removed using an oscillating saw, a Proxxon Micromot rotary tool (Proxxon GmbH, Föhren, Germany), hammer, chisel, and bone rongeur. This exposed the vertebral canal containing the spinal cord and spinal nerve roots. The spinal cord was transected cranial to C6 and caudal to T2 and subsequently removed.

All nerves belonging to the plexus were cut near their muscular entry points, allowing isolated examination of the spinal cord, spinal nerves, and peripheral branches. To ensure consistent identification of individual nerves after detachment from the surrounding musculature, each nerve was labelled with a plastic tag bearing an engraved number. During dissection and photographic documentation, these tags were temporarily placed adjacent to the corresponding nerve and subsequently reattached.

After removal of the surrounding epineurial connective tissue, the fascicles of each nerve were teased apart and assigned to their corresponding spinal root. Each step of the dissection was photographically documented.

## Measurements

Nerve diameters were measured after separation of the peripheral nerves but before removal of the epineurium and teasing of the fascicles. Measurements were taken with a standard metric ruler. Because the nerves were not perfectly round, the obtained values should be regarded as approximations, yet they provide important information about general nerve dimensions.

In the spinal nerves, the flattened morphology led to measurements that reflected the nerve's width rather than its diameter.

During allocation of peripheral nerve fascicles to their corresponding spinal nerves, no thickness measurements could be obtained; in these cases, the relative contribution was estimated. During dissection, specimens were stored in 10% saline solution at  $4-8^{\circ}\text{C}$ . When preparation exceeded eight weeks, 0.005% formaldehyde was added to the solution.

## Latex injection

In Alpaca No. 3 (50 ml) and in Alpaca No. 6 (80 ml), red latex milk (Lilalex from Tilutec, Clausthal-Zellerfeld, Germany) was injected into the arterial system via the right *arteria carotis communis* (*a. carotis communis*). The specimen was then stored under controlled conditions at  $4-8^{\circ}\text{C}$  for three days to allow complete polymerisation of the latex.

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## Photography

An Olympus Digital ED single-lens reflex camera (Olympus Corporation, Tokyo, Japan) equipped with an Olympus Zuiko Digital ED 14–42 mm f/3.5–5.6 lens and an Olympus Zuiko Digital 35 mm f/3.5 macro lens was used. A Hama PL CIR polarising filter (Hama GmbH & Co. KG, Monheim am Rhein, Germany), combined with linear polarising films (Screen-Tech e.K., Hamburg, Germany), placed in front of the light source, was used to reduce glare.

Images were taken against a black background using various tripods and subsequently processed with Adobe Photoshop CS5 (Adobe Inc., San Jose, CA, USA). Processing included darkening the background, adding a scale bar, and annotating anatomical structures using numbers, letters, and lines.

## Preparation of schematic illustrations

The schematic illustrations of the brachial plexus were produced entirely by the author. The author drew initial sketches by hand on paper based on the anatomical findings of the present study (Figure 1) and on data compiled from the literature (Figure 2). These drawings were subsequently digitised and

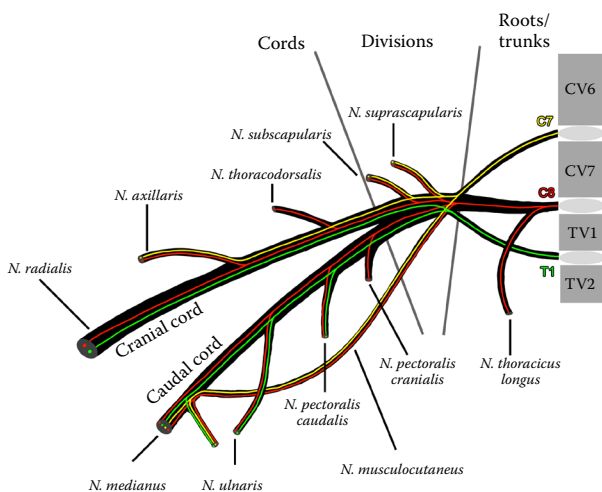


Figure 1. Schematic drawing illustrating the typical composition and organisation of the brachial plexus of the alpaca

C7, C8, T1 = ventral branches of the respective spinal nerve; CV6, CV7, TV1, TV2 = schematic drawing of respective cervical and thoracic vertebrae (dark grey) separated by symbolic intervertebral discs (light grey)

colourised using Adobe Fresco (Adobe Inc., San Jose, CA, USA) on an Apple iPad (Apple Inc., Cupertino, CA, USA) with an Apple Pencil. Final labelling and minor graphical adjustments were

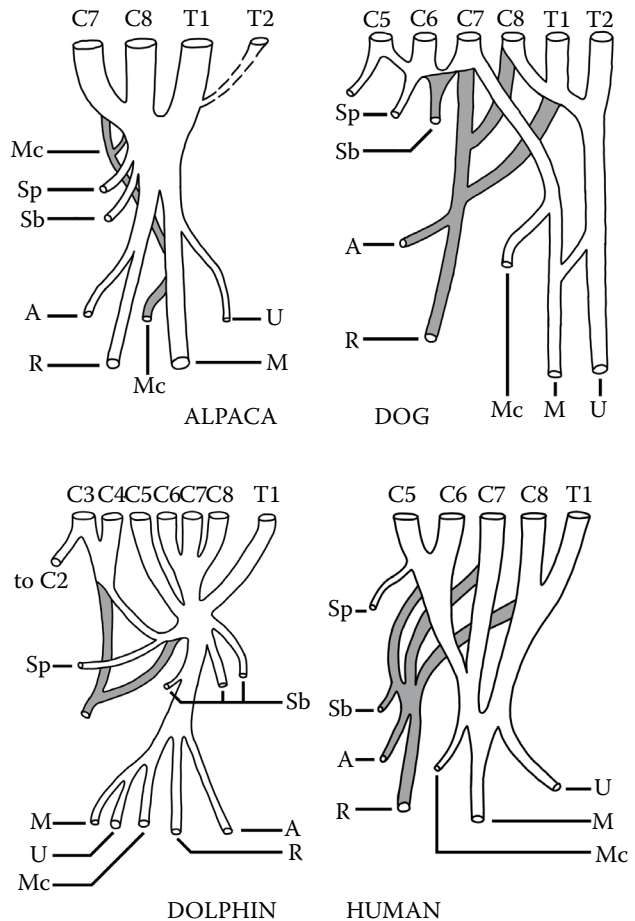


Figure 2. Comparative schematic representation of the origin and organisation of the brachial plexus in four species

The arrangement of spinal nerve contributions and major branches is illustrated for the alpaca, dog, dolphin, and human. The alpaca plexus is based on the present study; the dog and human plexuses are based on Miller (1934); and the dolphin plexus (Pacific white-sided dolphin, *Lagenorhynchus obliquidens*) is based on Sekiya et al. (2020). The overall graphic design was loosely inspired by Miller (1934), with substantial modifications in colour scheme and graphical representation. Lateral view of a left brachial plexus. Structures drawn in grey pass behind those drawn in white, representing a more medial course

A = *n. axillaris*; C2–T2 = ventral branches of the cervical and thoracic spinal nerves; M = *n. medianus*; Mc = *n. musculocutaneus*; R = *n. radialis*; Sb = *n. subscapularis*; Sp = *n. suprascapularis*; U = *n. ulnaris*

performed using Adobe Photoshop CS5 (Adobe Inc., San Jose, CA, USA). Anatomical terminology followed the Nomina Anatomica Veterinaria 2017 (International Committee on Veterinary Gross Anatomical Nomenclature 2017).

## RESULTS

In five of the six examined alpacas, the brachial plexus was formed by the ventral branches of the seventh and eighth cervical (C7, C8) and the first thoracic nerves (T1) (Figure 3). In one specimen, a minor contribution from the second thoracic nerve (T2) was observed. Compared with the other roots, the T2 contribution was very small. It fused rapidly with T1, indicating that the brachial plexus of the alpaca generally consists of three spinal roots, with occasional additional fibre bundles from a fourth spinal nerve.

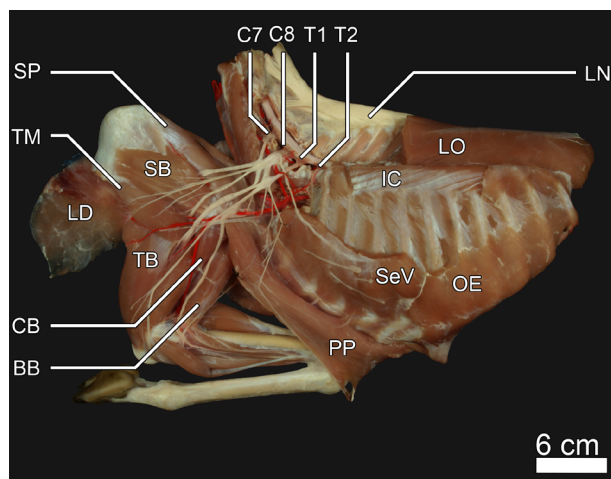


Figure 3. Photograph of alpaca No. 3 (left side, arterial system injected with red latex)

Lateral view of the caudal cervical region and thorax, and medial aspect of the left forelimb, which is reflected cranially. The dorsal epaxial musculature cranial to the sixth thoracic vertebra was removed. The vertebral canal was opened between the fifth cervical and the third thoracic vertebrae BB = *m. biceps brachii*; C7, C8, T1, T2 = ventral branches of the respective spinal nerves; CB = *m. coracobrachialis*; IC = *m. iliocostalis*; LD = *m. latissimus dorsi*; LN = *ligamentum nuchae*; LO = *m. longissimus pars thoracis*; OE = *m. obliquus externus abdominis*; PP = *m. pectoralis profundus*; SB = *m. subscapularis*; SeV = *m. serratus ventralis thoracis*; SP = *m. supraspinatus*; TB = *m. triceps brachii*; TM = *m. teres major*

The relative thickness and number of fibre bundles varied considerably among the roots. The eighth cervical nerve (C8) consistently represented the largest component, whereas C7 and T1 were smaller, with T1 always more prominent than C7. Measurements of root diameter in adult animals revealed values of 8–11 mm for C8, 4–5 mm for C7, and 6–8 mm for T1.

After emerging through the intervertebral foramina, the roots passed laterally through the *musculi scaleni* (*mm. scaleni*). This intermuscular gap, by which the plexus enters the axillary region and continues to the forelimb, is referred to as the interscalene space.

At this point, the roots continued as trunks: the cranial trunk derived from C7, the middle trunk from C8, and the caudal trunk from T1. In the specimen with four roots, the minor T2 component joined T1 before entering the interscalene space, forming the caudal trunk.

Unlike most domestic mammals, alpacas lack a *m. scalenus dorsalis*. Only the *mm. scaleni medius* (Figure 4: SM) and *ventralis* (Figure 4: SV) were present, the latter subdivided into dorsal, mid-

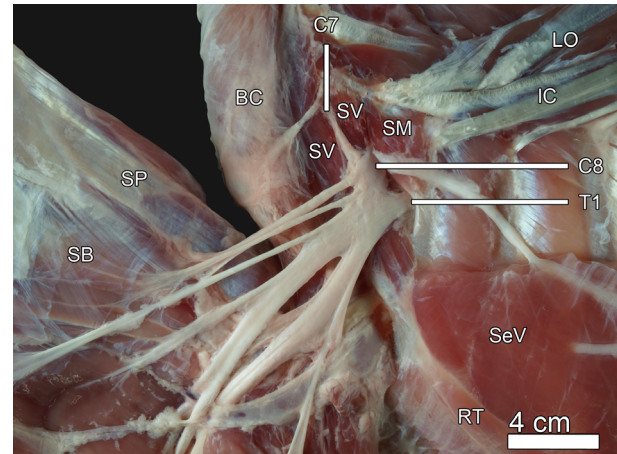


Figure 4. Photograph of alpaca No. 5

For better comparison, the image has been mirrored horizontally. Lateral view of the thoracic region cranial to the third rib. Emergence of the roots of the brachial plexus between the scalenus muscles and their course onto the right forelimb, which is reflected cranially

BC = *m. brachiocephalicus*; C7, C8, T1 = ventral branches of the respective spinal nerves; IC = *m. iliocostalis*; LO = *m. longissimus pars thoracis*; RT = *m. rectus thoracis*; SB = *m. subscapularis*; SeV = *m. serratus ventralis thoracis*; SM = *m. scalenus medius*; SP = *m. supraspinatus*; SV = *m. scalenus ventralis*

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dle, and ventral portions. The middle (Figure 4: C8) and caudal (Figure 4: T1) trunks passed between the *mm. scalenus medius* and *ventralis*, whereas the cranial trunk (Figure 4: C7) coursed between the dorsal and middle parts of the *m. scalenus ventralis*. This configuration resulted in a split interscalene space, a feature characteristic of alpacas.

After a short course to the medial aspect of the forelimb, the trunks interconnected and exchanged fibre bundles through divisions. Before this fibre exchange, the first peripheral branch, the *nervus thoracicus longus* (*n. thoracicus longus*) (Figure 5: 11), arose from the middle trunk (C8), exiting the interscalene space ventral to the *m. scalenus medius*. The remaining ten nerves of the brachial plexus originated either within the region of the fibre exchange or directly from the cords.

The cranial cord consisted of fibre bundles from C7, C8, and T1 and received one division from each trunk (Figure 1: Cranial Cord). The first peripheral

branches to separate were the *n. suprascapularis* (C7, C8) (Figure 5: 1) and the *nervi subscapulares* (*nn. subscapulares*) (C7, C8) (Figure 5: 2), both arising before distinct cord formation but assignable to the cranial cord by root composition.

From the established cord, the *n. thoracodorsalis* (C8) (Figure 5: 3) branched first, followed by the *n. axillaris* (C7, C8) (Figure 5: 4). These two nerves were closely associated but could be separated by blunt dissection. After the branching of the *n. axillaris*, C7 fibre bundles were no longer present in the cranial cord, which continued distally as the *n. radialis* (C8, T1) (Figure 5: 5).

The caudal cord consisted of fibre bundles from C8 and T1 and received one division from both the middle and caudal trunks (Figure 1: Caudal Cord). The first branch was the *n. pectoralis cranialis* (C8) (Figure 5: 9), followed immediately by the *n. pectoralis caudalis* (C8, T1) (Figure 5: 7). More distally, the *n. ulnaris* (C8, T1) (Figure 5: 6) diverged,

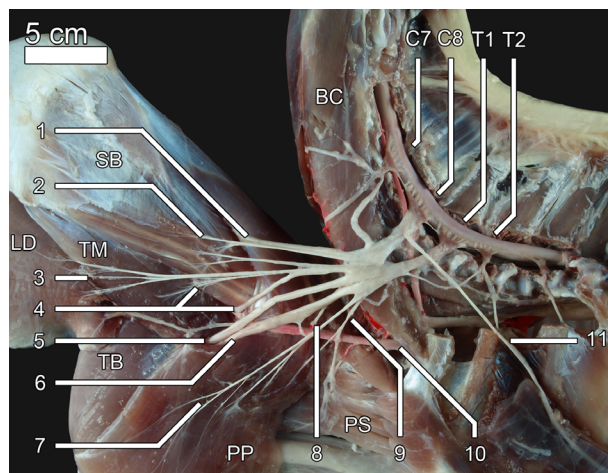


Figure 5. Photograph of alpaca No. 6 (left side)

Lateral view of the caudal cervical and cranial thoracic region, and proximomedial aspect of the left forelimb, which is reflected cranially. The dorsal epaxial musculature was removed. The vertebral canal was opened between the fifth cervical and the fourth thoracic vertebrae. The *m. pectoralis profundus* has been detached from the sternum

1 = *n. suprascapularis*; 2 = *nn. subscapulares*; 3 = *n. thoracodorsalis*; 4 = *n. axillaris*; 5 = *n. radialis*; 6 = *n. medianus* and *n. ulnaris*; 7 = *n. pectoralis caudalis*; 8 = *n. musculocutaneus*; 9 = *n. pectoralis cranialis*; 10 = *a. axillaris*; 11 = *n. thoracicus longus*; BC = *m. brachiocephalicus*; C7, C8, T1, T2 = segment of the spinal cord releasing the respective spinal nerve; LD = *m. latissimus dorsi*; PP = *m. pectoralis profundus*; PS = *m. pectoralis superficialis*; SB = *m. subscapularis*; TB = *m. triceps brachii*; TM = *m. teres major*

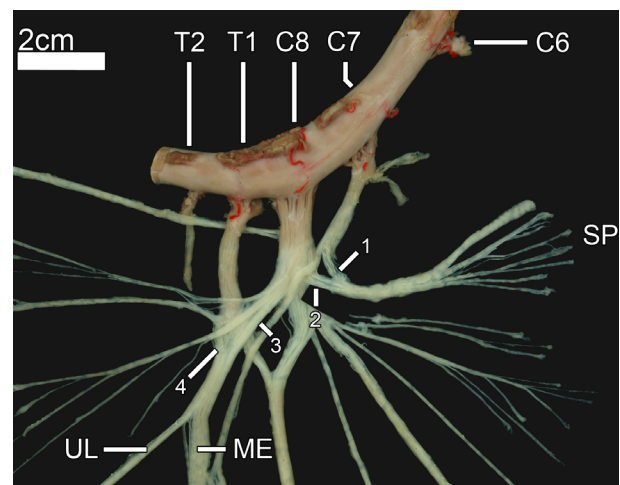


Figure 6. Photograph of the proximal part of the left brachial plexus of alpaca No. 3 (medial view)

Composition of the *n. suprascapularis*, *n. medianus*, and *n. ulnaris*. The spinal cord was transected cranial to C6 and caudal to T2 and removed from the vertebral canal. The peripheral nerves were transected close to their target regions

C6 = stump of the sixth cervical spinal nerve; 1 = C7 fibre contribution to the suprascapular nerve; 2 = C8 fibre contribution to the suprascapular nerve; 3 = C8 fibre contribution to the median and ulnar nerves; 4 = T1 fibre contribution to the median and ulnar nerves; C7, C8, T1, T2 = segment of the spinal cord releasing the respective spinal nerves; ME = *n. medianus*; SP = *n. suprascapularis*; UL = *n. ulnaris*

and the remaining fibre bundles continued as the median nerve (Figure 5: 6).

The caudal division of the cranial trunk (C7) differed from the others in its course. It passed medially over the middle trunk (C8) and its divisions in a caudodistal direction. In five of six specimens, it also received fibre bundles from the middle trunk. This branch reached the *a. axillaris* (Figure 5: 10), where it formed the *ansa axillaris*, looping around the artery and connecting with the caudal cord and the *n. medianus*. The caudal division of the cranial trunk, therefore, corresponded to the *n. musculocutaneus* (Figure 5: 8). Through the *ansa axillaris*, fibre exchange occurred between the *n. medianus* and *n. musculocutaneus*, resulting in both nerves containing fibre bundles from all three spinal nerves (C7, C8, T1).

### *Nervus suprascapularis*

In all six examined animals, the *n. suprascapularis* was composed of fibre bundles from the ventral

branches of the seventh (C7) and eighth cervical nerves (C8) (Figure 6: 1+2). The diameter ranged from 4–6 mm and 3 mm in the juvenile. C8 predominated in most limbs, although in one case the C7 contribution was slightly greater.

### *Nervi subscapulares*

The *nn. subscapulares* likewise arose from the ventral branches of C7 and C8 (Figure 7: 1+2). Their diameter measured 2–4 mm in adults and 1.5 mm in the juvenile. The relative contribution of the two spinal nerves to the *nn. subscapulares* was balanced: in three limbs, C7 was dominant; in three, C8 predominated; and in three, both contributions were nearly equal.

### *Nervus thoracodorsalis*

The *n. thoracodorsalis* represented the first branch of the cranial cord, whereas the *nn. suprascapularis*

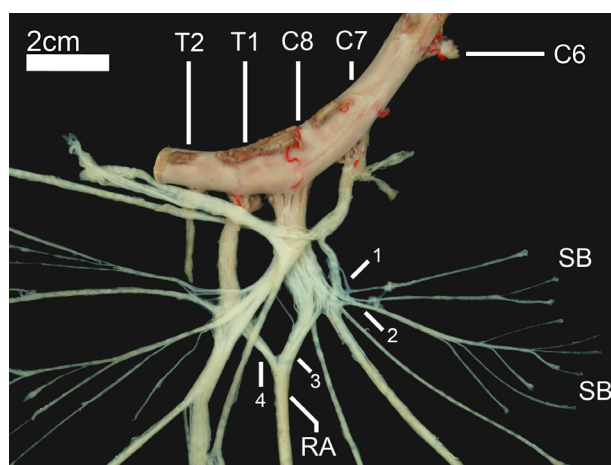


Figure 7. Photograph of the proximal part of the left brachial plexus of alpaca No. 3 (medial view) Composition of the *n. radialis* and *nn. subscapulares*. The spinal cord was transected cranial to C6 and caudal to T2 and removed from the vertebral canal. The peripheral nerves were transected close to their target regions 1 = C7 fibre contribution to the subscapular nerve; 2 = C8 fibre contribution to the subscapular nerve; 3 = C8 fibre contribution to the radial nerve; 4 = T1 fibre contribution to the radial nerve; C6 = stump of the sixth cervical spinal nerve; C7, C8, T1, T2 = segment of the spinal cord releasing the respective spinal nerves; RA = *n. radialis*; SB = *nn. subscapulares*

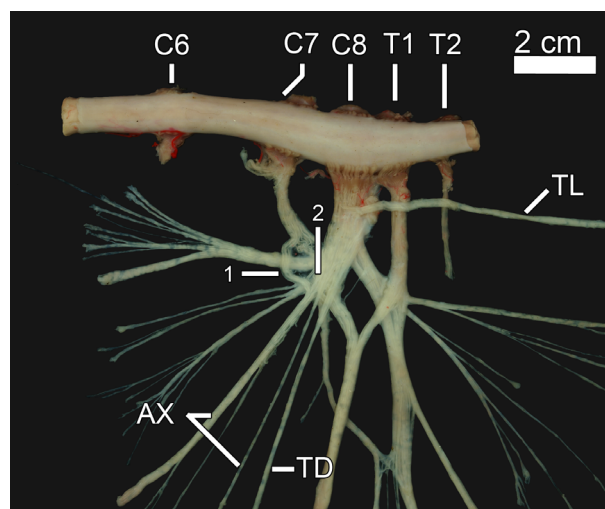


Figure 8. Photograph of the proximal part of the left brachial plexus of alpaca No. 3 (lateral view) Composition of the *nn. axillaris*, *thoracodorsalis* and *thoracicus longus*. The spinal cord was transected cranial to C6 and caudal to T2 and removed from the vertebral canal. The peripheral nerves were transected close to their target regions 1 = C7 fibre contribution to the axillary nerve; 2 = C8 fibre contribution to the axillary nerve; AX = *n. axillaris*; C6, C7, C8, T1, T2 = segment of the spinal cord releasing the respective spinal nerves; TD = *n. thoracodorsalis*; TL = *n. thoracicus longus*

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and *subscapulares* branched off before the cord was formed. In four of six animals, the nerve derived exclusively from C8 fibre bundles (Figure 8: TD). The diameter ranged from 1.5–4 mm in adults and 1 mm in the juvenile. In one limb, a minor contribution from C7 was observed. In the individual in which T2 contributed to the brachial plexus (Figure 5), the nerve received approximately an equal number of fibre bundles from C8 and T1.

### *Nervus axillaris*

The *n. axillaris* branched next from the cranial cord, and in all specimens arose from fibre bundles of C7 and C8 (Figure 8: 1+2). The diameter ranged from 4–5 mm in adults and measured 2.5 mm in the juvenile. In one limb, C7 predominated, in another the contributions were balanced, and in the remaining seven limbs, C8 accounted for at least two-thirds of the fibre bundles.

### *Nervus radialis*

The *n. radialis* represented the terminal continuation of the cranial cord, originating consistently from the ventral branches of C8 and T1 (Figure 7: 3+4). The diameter measured 5–8 mm in adults and 4 mm in the juvenile. In all but one animal, C8 contributed the majority of fibre bundles. In one individual, the composition was balanced between C8 and T1.

### *Nervus thoracicus longus*

In all animals, the *n. thoracicus longus* branched from the plexus shortly before the trunks emerged from the scalene gap, originating exclusively from the middle trunk (C8) (Figure 8: TL). Its diameter ranged from 2–4 mm.

### *Nervus musculocutaneus*

In alpacas, the *n. musculocutaneus* corresponded to the caudal division of the cranial trunk. It consisted mainly of fibre bundles from C7, but in eight of nine examined limbs, it also received additional fibre bundles from C8 (Figure 9: 1+2). The diameter measured 2–4 mm in all animals. The nerve arose

far cranially and coursed caudodistally, crossing over the middle cord medially. At the level of the shoulder joint, the *n. musculocutaneus* (lateral to the *a. axillaris*) united with the *n. medianus* (medial to the *a. axillaris*) to form the *ansa axillaris*. Because of this communication, the *n. medianus* distal to the *ansa axillaris* contained fibre bundles from all three spinal nerves (C7, C8, T1). The *n. musculocutaneus* terminated in *rami musculares proximales* (*rr. musculares proximales*) and could no longer be distinguished distally from the *m. coracobrachialis* (Figure 10). Notably, fibre bundles typically attributed to the *n. musculocutaneus* in other domestic mammals were traced to the *n. medianus* and *n. ulnaris* in the present material; these findings are not discussed in detail here, as they pertain primarily to the course and distribution of the plexus nerves.

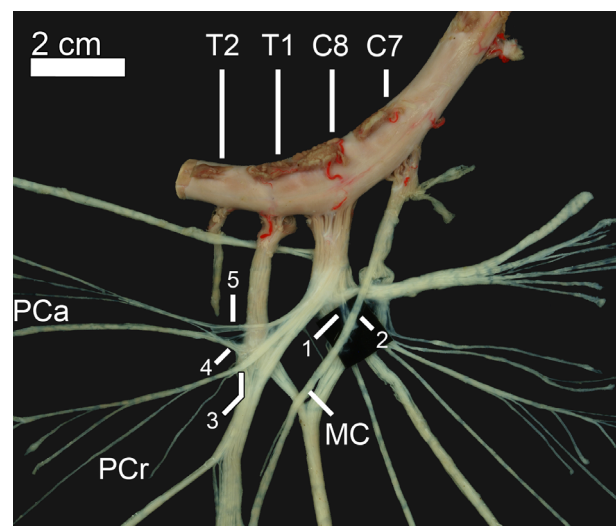


Figure 9. Photograph of the proximal part of the left brachial plexus of alpaca No. 3 (medial view)

Composition of the *nn. pectoralis cranialis, caudalis* and *musculocutaneus*. The spinal cord was transected cranial to C6 and caudal to T2 and removed from the vertebral canal. The peripheral nerves were transected close to their target regions

1 = C8 fibre contribution to the musculocutaneus nerve; 2 = C7 fibre contribution to the musculocutaneus nerve; 3 = C8 fibre contribution to the cranial pectoral nerve; 4 = T1 fibre contribution to the caudal pectoral nerve; 5 = C8 fibre contribution to the caudal pectoral nerve; C6 = stump of the sixth cervical spinal nerve; C7, C8, T1, T2 = segment of the spinal cord releasing the respective spinal nerves; MC = *n. musculocutaneus*; PCa = *n. pectoralis caudalis*; PCr = *n. pectoralis cranialis*

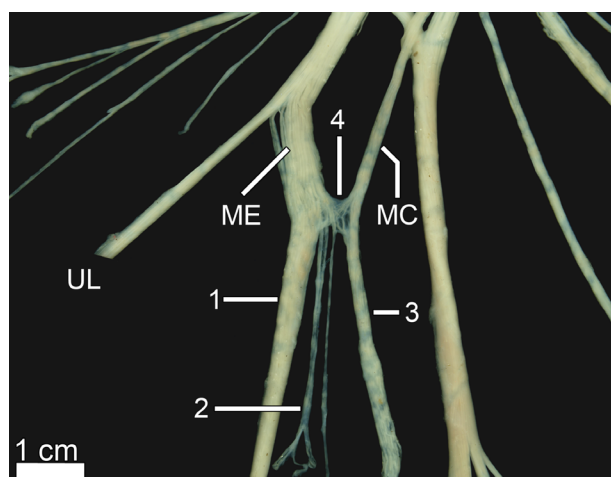


Figure 10. Medial view of the isolated left brachial plexus of alpaca No. 3 showing the *ansa axillaris* and the composition of the proximal muscular branches (*rr. musculares proximales*)

1 = median nerve after fibre exchange with the musculocutaneous nerve; 2 = *rr. musculares proximales*, branches of the median nerve to the coracobrachialis muscle; 3 = *rr. musculares proximales*, branches of the musculocutaneous nerve to the biceps brachii muscle; 4 = *ansa axillaris*; MC = *n. musculocutaneus*; ME = *n. medianus*; UL = *n. ulnaris*

### *Nervus pectoralis cranialis*

The *n. pectoralis cranialis* was the first branch of the caudal cord, originating on the medial aspect of the brachial plexus. In eight of nine limbs, it consisted exclusively of fibre bundles from C8 (Figure 9: 3). In one limb, from the specimen with a T2 contribution, a very minor addition from T1 was present. The diameter measured 2–3 mm in adults and 1 mm in the juvenile.

### *Nervus pectoralis caudalis*

The *n. pectoralis caudalis*, the second medial branch of the caudal cord, was composed of fibre bundles from C8 and T1 in all but one animal (Figure 9: 4+5). Its diameter measured 2–4 mm in adults and 1.5 mm in the juvenile. In the specimen with four spinal roots, the nerve derived mainly from T1, with minor input from C8 and T2. In all other individuals, C8 and T1 contributed variably.

### *Nervus thoracicus lateralis*

Within the scope of this study, it was further determined that the *n. thoracicus lateralis* does not originate directly from the brachial plexus in the alpaca. Instead, a nerve arising from the second or third thoracic nerve was identified, coursing toward the region between the *mm. latissimus dorsi*, *pectoralis profundus*, and *triceps brachii*. This nerve most likely corresponds anatomically to the *n. thoracicus lateralis* or more precisely to its respective derivative, the *n. intercostobrachialis*, as described above.

### *Nervus ulnaris*

The *n. ulnaris* branched off last from the caudal cord, before the latter continued distally as the *n. medianus*. It consisted primarily of T1 fibre bundles (Figure 6: UL). In five limbs examined, small C8 contributions were present, though generally minor, except in one specimen where they were clearly more substantial. Thus, T1 represented the predominant component in the examined limbs. In the individual with T2 involvement, a few T2 fibre bundles were added to the otherwise dominant T1 component. The diameter ranged from 3–5 mm in all animals examined.

### *Nervus medianus*

The *n. medianus* represented the terminal continuation of the caudal cord, composed in this region primarily of C8 and T1 fibre bundles (Figure 6: 3+4). Following fibre exchange with the *n. musculocutaneus* within the *ansa axillaris*, the *n. medianus* also incorporated fibre bundles from C7 and C8, so that distal to the loop, it contained fibre bundles from all three spinal nerves (C7, C8, T1) (Figure 10: 1). The C8 component generally predominated, although in both limbs of one animal, C7 and C8 contributions were approximately equal. The diameter measured 6–8 mm in adults and 4 mm in the juvenile specimen.

The origin and spinal nerve composition of each individual nerve of the brachial plexus are summarised in Table 2, which also provides the corresponding innervation areas identified for each individual nerve.

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Table 2. Typical spinal nerve composition and innervation areas of the nerves of the brachial plexus in the alpaca

| Nerve                       | Origin     | Distribution                                                                                                                                                                                                                                                                    |
|-----------------------------|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Suprascapularis</i>      | C7, C8     | <i>m. supraspinatus</i><br><i>m. infraspinatus</i>                                                                                                                                                                                                                              |
| <i>Subscapulares</i>        | C7, C8     | <i>m. subscapularis</i>                                                                                                                                                                                                                                                         |
| <i>Thoracodorsalis</i>      | (C7), C8   | <i>m. latissimus dorsi</i>                                                                                                                                                                                                                                                      |
| <i>Thoracicus longus</i>    | C8         | <i>m. serratus ventralis thoracis</i>                                                                                                                                                                                                                                           |
| <i>Axillaris</i>            | C7, C8     | <i>m. teres major</i><br><i>m. teres minor</i><br><i>m. subscapularis</i> (caudal border)<br><i>m. deltoideus</i><br><i>m. brachiocephalicus</i><br>lateral cutaneous area of the brachium<br>cranial cutaneous area of the antebrachium                                        |
| <i>Radialis</i>             | C8, T1     | <i>m. triceps brachii</i><br><i>m. extensor digitorum lateralis</i><br><i>m. extensor digitorum communis</i><br><i>m. extensor carpi radialis</i><br><i>m. extensor carpi ulnaris</i><br>laterocranial cutaneous area of the antebrachium<br>dorsal cutaneous area of the manus |
| <i>Musculocutaneus</i>      | C7, C8     | <i>m. biceps brachii</i><br>( <i>m. coracobrachialis</i> )                                                                                                                                                                                                                      |
| <i>Medianus</i>             | C7, C8, T1 | <i>m. coracobrachialis</i><br>( <i>m. biceps brachii</i> )<br><i>m. brachialis</i><br><i>m. flexor carpi radialis</i><br><i>m. flexor digitorum superficialis</i><br><i>m. flexor digitorum profundus</i><br>palmar cutaneous area of the digits                                |
| <i>Ulnaris</i>              | (C8), T1   | <i>m. flexor carpi ulnaris</i><br><i>caput humerale m. flexor digitorum profundus</i><br>medial and caudal skin of the antebrachium<br>palmar cutaneous area of the manus                                                                                                       |
| <i>Pectoralis cranialis</i> | C8         | <i>m. pectoralis superficialis</i><br>cranial part of <i>m. pectoralis profundus</i>                                                                                                                                                                                            |
| <i>Pectoralis caudalis</i>  | C8, T1     | <i>m. pectoralis profundus</i>                                                                                                                                                                                                                                                  |

## DISCUSSION

### Origin of the brachial plexus

In five of the six alpacas examined, the brachial plexus was formed by the ventral branches of the seventh and eighth cervical (C7, C8) and the first thoracic (T1) nerves. This finding confirms that these three spinal nerves represent the principal components of the plexus. In the remaining indi-

vidual (Figure 5), a minor contribution from the second thoracic nerve (T2) was present (Figure 2: Alpaca).

The only previous description of the brachial plexus in alpacas, provided by Goshima Watanabe (1976), likewise reported C7, C8, and T1 as major contributors, but also described consistent participation of C6 and T2, concluding that the plexus extended from C6 to T2. However, C6 and T2 were markedly thinner than C7–T1, and their fibre bun-

dles quickly fused with adjacent roots. It should be noted that this description represents the only available account of the origin of the brachial plexus in alpacas. Yet, it was published in Spanish and is not publicly accessible. In addition, *Gotz (2019)* mentioned the brachial plexus of the alpaca in her doctoral thesis on the topography of the forelimb. Still, the corresponding section was very brief and did not include a detailed description of the plexus origin.

In the closely related dromedary, C6, C7, and T1 constituted the main components, with occasional minor branches from T2 (*Smuts and Bezuidenhout 1987b*). Thus, in camelids, the brachial plexus generally comprises three spinal nerves, with sporadic fine connections from a preceding or succeeding segment.

In mammals with shorter necks, such as dogs, ruminants, and pigs, the plexus typically arises from four to five spinal nerves (*Seiferle and Boehme 2003; Salomon 2020b*). In ruminants, the ventral branches of C6–T1 are consistently involved, and in over half of the cases, a fine branch from T2 also contributes (*Reimers 1925*). The dog provides a well-studied comparison: in 58.6% of dogs, the plexus arises from C6–T1; in 20.6%, C5 participates; in 17.2%, T2 contributes; and in 0.03%, both C5 and T2 are present (*Allam et al. 1952*) (*Figure 2: Dog*). *Miller (1934)* confirmed these findings, noting that the C5 branch, when present, was extremely fine.

In contrast, aquatic mammals with short, compact necks, such as dolphins and porpoises (*Willems et al. 2021; Goel et al. 2021*), have a greater number of contributing roots. Their brachial plexus may include up to eight spinal nerves (C4–T1), with occasional fibre bundles from C3 or T2 (*Cunningham 1877; Sekiya et al. 2020*) (*Figure 2: Dolphin*).

A similar pattern to that observed in alpacas is found in the brachial plexus of giraffids. This family includes the giraffe, renowned for the longest neck among mammals, and the okapi, considered an evolutionary intermediate between short-necked ruminants and the long-necked giraffe (*Danowitz and Solounias 2015*). In the okapi, the plexus is formed by C6–T1, as in other ruminants, but the roots of C7, C8, and T1 are particularly prominent. By contrast, the contribution from C6 is weak and elongated, joining C7 proximally in the plexus (*Endo et al. 2009*). It has therefore been suggested that the functional importance of C6 decreases in the okapi, while C7 assumes

a greater role, resulting in a “cranially simplified” plexus. *Solounias (1999)* likewise described C7, C8, and T1 as the principal components of the okapi plexus, but he did not detect a root from C6. Instead, he observed a fine branch from T2 that joined T1 proximally. Both accounts agree that the plexus arose mainly from three spinal nerves, with the possibility of minor fibre bundle contributions from adjacent segments.

In the giraffe, the brachial plexus is further simplified. The main contribution derives only from the eighth cervical and the first thoracic nerves. C7 is markedly thinner and rapidly merges with C8, while T2 likewise fuses with T1 at an early stage. Thus, the formation of the giraffe’s brachial plexus can essentially be reduced to two spinal nerves, each maintaining fine connections with the adjacent roots. Accordingly, the giraffe plexus is described as both cranially and caudally simplified (*Solounias 1999; Endo et al. 2009*). These findings on brachial plexus morphology across selected mammalian species highlight not only interspecific but also intraspecific variation. Such minor differences in the origin and arrangement of the plexus are also well recognised in human anatomy (*Johnson et al. 2010*). It has been estimated that more than half of the human population shows deviations from the “classical” brachial plexus configuration. *Uysal et al. (2003)* reported that in 53.5% of 200 foetal specimens, the organisation of the plexus deviated from the typical description. Nevertheless, the number of prominently developed roots uniting to form the plexus remains relatively constant. When an additional neighbouring spinal nerve participates, its contribution is usually minimal, and the fine communicating branch fuses with an adjacent major root of the brachial plexus.

A comparison of the brachial plexus composition among the species examined reveals a clear correlation between neck length and the number of spinal nerves contributing to plexus formation. Cervical length varies considerably among mammals depending on body size, locomotor demands, habitat, and species-specific behaviour (*Aba et al. 2010; Arnold et al. 2017; Boonsri et al. 2021*). Giraffids and camelids represent notable exceptions, exhibiting disproportionately elongated cervical spines, primarily due to elongation of vertebrae C3–C6 (*Arnold et al. 2017; Waringo 2018*). In alpacas, this results in a substantial distance between the exit of C6 at the sixth cervical vertebra and the fore-

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limb. This may explain why C6 is less likely to contribute to plexus formation, whereas T2, exiting only a few centimetres caudal to T1, is more frequently involved. The results of the present study support this interpretation, even though Goshima Watanabe (1976) described consistent contributions from both C6 and T2. However, discrepancies between the textual descriptions and the drawings and photographs in the appendix of his dissertation complicate the interpretation of that work.

Nevertheless, the giraffe's neck length is exceptional even among long-necked mammals. The elongation of the cervical vertebrae far exceeds that of any other extant ungulate, although this factor alone does not account for the extreme length of the neck (Danowitz and Solounias 2015). Normally, the transition between the widely spaced articular processes of the cervical vertebrae and the closely positioned processes of the thoracic vertebrae is established by T1. In the giraffe, however, T2 represents the transitional vertebra, making it the only known mammal in which this occurs (Lankester 1908; Solounias 1999; Danowitz and Solounias 2015). This “cervicalisation” of the first thoracic vertebra is also reflected in the position of the brachial plexus. Typically, the plexus is centred around C7. In the giraffe, however, the centre is shifted caudally by one vertebra, and the main roots C8 and T1 form the plexus around the level of the first thoracic vertebra (Solounias 1999; Endo et al. 2009).

In summary, cervical length in mammals is inversely correlated with the number of spinal nerves contributing to the brachial plexus. In aquatic mammals with short necks, up to eight spinal nerves form the plexus; in most domestic mammals, four to five roots are involved; in camelids and the okapi, with relatively long necks, three to four roots participate; and in the giraffe, only two major spinal nerves remain as the principal contributors (Figure 11). Connolly and Auchincloss (2021) noted that anomalies of the cervical vertebrae in humans can likewise lead to a cranially or caudally shifted plexus and variation in the number of contributing spinal nerves, further underscoring the relationship between cervical anatomy and plexus composition.

In this context, future research would benefit from histological and anatomical comparisons of the plexus-forming spinal cord segments across different mammalian taxa. An important question is the extent to which cervical spine elongation is accompanied by changes in spinal cord

length. Is the degree of development of the *intumescentia cervicalis* – the cervical enlargement of the spinal cord at the cervicothoracic junction from which the plexus-forming spinal nerves arise (Seiferle and Boehme 2003) – comparable to that of other mammals? Do long-necked species possess a greater number of neurons in this region of the spinal cord? Or is the cervical enlargement similar in size, but, owing to the elongated neck, fewer adjacent intervertebral foramina lie within this segment, thereby reducing the number of spinal nerves available for plexus formation?

### Transition of the brachial plexus to the forelimb

In domestic mammals, the roots of the brachial plexus typically emerge immediately cranial to the

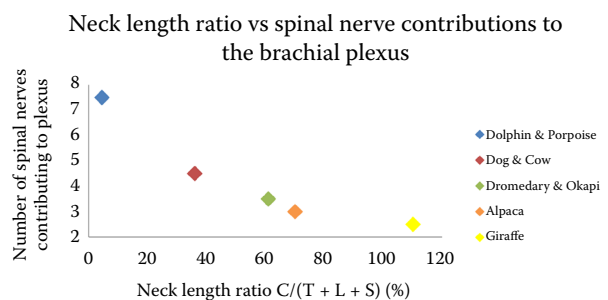


Figure 11. Diagram showing the relationship between the cervical-to-postcervical vertebral length ratio and the number of spinal nerves contributing to the brachial plexus in selected mammalian species

The neck length ratio represents the proportion of the length of the cervical vertebral column (C) relative to the length of the remaining vertebral column – comprising the thoracic (T), lumbar (L), and sacral (S) vertebrae – expressed in percent. Species with a relatively short cervical region (e.g., dolphins and porpoises) show higher numbers of contributing spinal nerves, whereas species with a long cervical region (e.g., giraffe) exhibit fewer contributing spinal nerves. A y-axis value ending in “.5” indicates morphological variation within the species, where individuals typically show either the higher or the lower adjacent number of contributing spinal nerves

Data compiled from the present study and published literature (Cunningham 1877; Reimers 1925; Smuts and Bezuidenhout 1987b; Solounias 1999; Buchholtz and Schur 2004; Endo et al. 2009; de Lahunta and Evans 2013; Sekiya et al. 2020; Belyaev et al. 2021)

first rib between the *m. longus colli* and the scalene muscles (Seiferle and Boehme 2003). Following their emergence, the plexus components may organise into the trunk-division-cord pattern described in the introduction, although the degree to which this organisation can be distinguished varies considerably among species. This trunk-division-cord organisation is most widely described in human medicine and primates, but has also been applied to the brachial plexus of monotremes (Koizumi and Sakai 1997), the red squirrel (*Sciurus vulgaris*) (Aydin 2011), and the hippopotamus (*Hippopotamus amphibius*) (Yoshitomi et al. 2012). In many mammals, such as the dog, the participation of numerous spinal nerves, irregular branching, and variable formation obscure a clear distinction of trunks and cords (Miller 1934).

By contrast, the alpaca plexus arose from only three main roots, from which three trunks were consistently formed. Owing to this relatively simple branching pattern, the plexus can be described in a manner comparable to human anatomy. Although Goshima Watanabe (1976) did not explicitly use the trunk–cord terminology, he described trunk-like structures formed after the fusion of ventral branches from adjacent spinal nerves. He reported a common origin of the *nn. suprascapularis* and *subscapulares* from C7 and C8, but did not designate these as a trunk. This agrees with the present finding that both nerves branch off before cord formation. From the junction of C8 and T1, he described a dorsocranial strand giving rise to the *nn. axillaris* and *radialis*, and a ventrocaudal strand from which the *nn. medianus*, *musculocutaneus*, and *ulnaris* originated. These correspond to the cranial and caudal cords in the present description.

Because the roots of the plexus pass through the space between the *mm. scaleni*, this region is often referred to as the scalene gap. The *mm. scaleni* are composed of up to three distinct muscles: *m. scalenus dorsalis*, *m. scalenus medius*, and *m. scalenus ventralis*. In alpacas, as in horses and sheep, the *m. scalenus dorsalis* is absent (Seiferle and Frewein 2004; Waringo 2018). In carnivores, the *m. scalenus ventralis* is lacking, so that the plexus roots do not emerge between the *mm. scaleni*, but rather ventral to the *m. scalenus medius* (Getty 1975; Seiferle and Frewein 2004). In other domestic mammals, the plexus emerges ventral to the *m. scalenus medius* and dorsal to the *m. scalenus ventralis* (Seiferle and Frewein 2004; Salomon 2020a).

Waringo (2018) noted that in the alpaca, C7 passed between the dorsal and middle portions of a tripartite *m. scalenus ventralis* before joining the remaining roots to form the trunks. This split scalene gap was confirmed in all specimens examined in the present study. Such a separated exit of plexus roots is rarely reported in other species. Getty (1975) described the roots as traversing the *m. scalenus ventralis* in pigs and ruminants, but without clarifying whether part of the plexus also emerged between *m. scalenus medius* and *ventralis*. A true split gap has, however, been documented in goats (Kamali 2025) and in a Sumatran rhinoceros (Backus et al. 2016). In goats, C6 and C7 passed separately from C8 and T1 through the last fascicle of the *m. scalenus ventralis*. In the rhinoceros, the cranial trunk (C5–C7) and the caudal trunk (C8–T2) emerged separately, divided by the *m. scalenus medius*.

Connolly and Auchincloss (2021) described a split scalene gap in humans as an anatomical variant, reflecting the developmental process whereby the brachial plexus divides the scalene musculature into anterior and posterior divisions. The cranial roots of the plexus may exit independently of the more caudal roots, either between or through the anterior scalene muscle (Connolly and Auchincloss 2021). The human anterior scalene muscle corresponds functionally to the ventral scalene muscle in animals. Notably, this anatomical configuration, considered a human variation, was consistently observed in all examined alpacas in the present study.

This finding in alpacas may be of particular clinical relevance for brachial plexus blocks using local anaesthetics, particularly in the context of various surgical procedures of the forelimb, such as shoulder luxation repair (Santoro and Kaartinen 2022; Citarella et al. 2023). Although the overall situation resembles that of ruminants, the separate emergence of C7 at a more cranial position could predispose to incomplete anaesthesia. Citarella et al. (2023) performed an ultrasound-guided plexus block by injecting 0.25% bupivacaine into the scalene gap. Although generally effective, incomplete blockade of the cranial plexus-forming spinal nerves was suspected because of spontaneous limb movements observed during surgery. This observation supports the hypothesis that the split exit may increase the risk of incomplete anaesthesia. In such cases, placement of anaesthetic at both

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exit points could be considered. Conversely, based on anatomical considerations, the separation of the C7 root at the proximal part of the ventral scalene muscle may also serve as a useful landmark for ultrasound-guided injection. The exit point of the C7 trunk lay cranial to the limb contour, in contrast to the more caudal trunks. It may be identified a few centimetres cranial to the forelimb along an imaginary line between the acromion and the mid-cervical region (Figure 12B: C7). At this level, the nerve was covered only by the *m. brachiocephalicus*, which may facilitate sonographic identification. From this region, the cranial trunk can be traced caudally into the axilla, where the main exit between the *m. scalenus medius* and *ventralis* was located.

These considerations are based solely on anatomical observations, and further experimental and clinical studies are required to evaluate their applicability.

Reports of brachial plexus blocks in alpacas remain scarce. In addition to the ultrasound-guided interscalene block described by Citarella et al. (2023), an ultrasound-guided axillary block has also been reported (Santoro and Kaartinen 2022). In both studies, local plexus blocks were considered safe and effective techniques for intra- and postoperative analgesia. Ward et al. (2021) further

demonstrated that a nerve stimulator-guided block of the sciatic and femoral nerves in the hindlimb can be more practical than ultrasound guidance under field conditions, with similarly favourable results. They emphasised the importance of multimodal analgesia in alpacas, as these animals often mask signs of pain and are predisposed to stress-related gastric ulcers. Moreover, since alpacas in the EU are frequently classified as food-producing animals, strict drug regulations must be observed (Ward et al. 2021).

Comparable benefits of ultrasound-guided plexus blockade have already been shown in ruminants. This approach permits surgical interventions on the front limb under deep sedation rather than general anaesthesia. It is feasible under field conditions with portable ultrasound devices, which are now widely available in farm animal practice (Iwamoto et al. 2012). A retrospective study of 193 goats demonstrated increased perioperative mortality under general anaesthesia compared with horses, dogs, and cats (Ringer and Bettschart-Wolfensberger 2023). These findings suggest that elevated anaesthetic risk may be a general problem in ruminants and camelids. By avoiding general anaesthesia, plexus blocks may substantially reduce the risks of regurgitation and tympany of the forestomach.

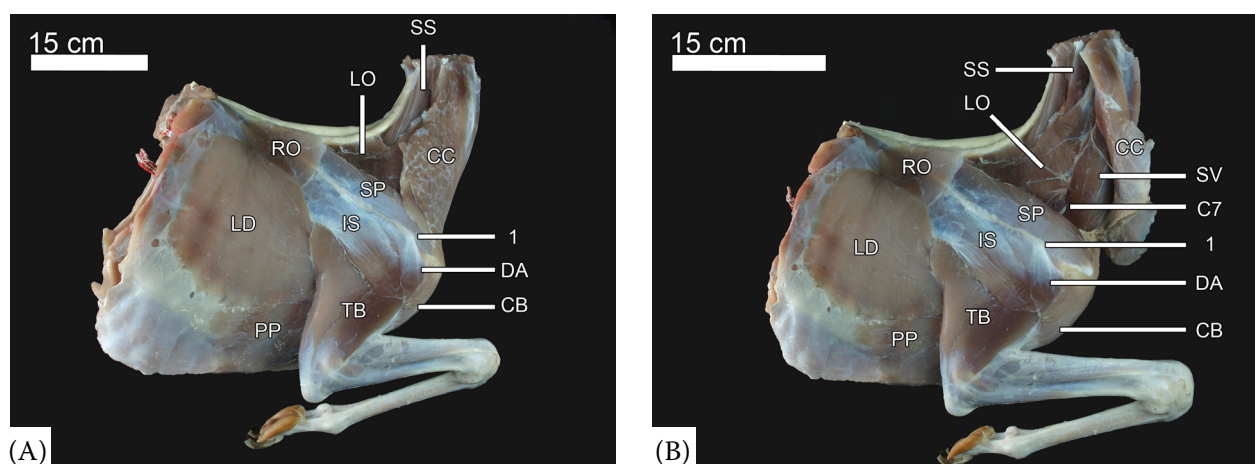


Figure 12. Photographs showing the emergence and course of the C7 root of the brachial plexus to the forelimb in the alpaca No. 5 in physiological limb position

Right side of the thorax and caudal cervical region with the right forelimb. The *m. trapezius* was removed. (A) Overall view. (B) After cranial reflection of the *m. cleidocephalicus*

1 = acromion; C7 = C7 root of the brachial plexus; CB = *m. cleidobrachialis* of the *m. brachiocephalicus*; CC = *m. cleidocephalicus* of the *m. brachiocephalicus*; DA = *m. deltoideus pars acromialis*; IS = *m. infraspinatus*; LD = *m. latissimus dorsi*; LO = *m. longissimus*; PP = *m. pectoralis profundus*; RO = *m. rhomboideus pars superficialis*; SP = *m. supraspinatus*; SS = *m. semispinalis*; SV = *m. scalenus ventralis*; TB = *m. triceps brachii*

### ***Nervus thoracicus longus***

In domestic mammals, the origin of the *n. thoracicus longus* is relatively consistent, arising mainly from the ventral branches of C7 or C8 (Reimers 1925; Seiferle and Boehme 2003). In the dog, it derives exclusively from C7 (Reimers 1925; de Lahunta and Evans 2013). In alpacas, as also reported by Goshima Watanabe (1976), the nerve was composed solely of fibre bundles from C8. In the closely related dromedary, an additional contribution from C7 has been described (Smuts and Bezuidenhout 1987b).

### ***Nervus thoracodorsalis***

In domestic mammals, the *n. thoracodorsalis* arises primarily from C8, with occasional contributions from adjacent spinal nerves (Reimers 1925; Seiferle and Boehme 2003). In alpacas, Goshima Watanabe (1976) reported a contribution from C7 in addition to C8. In the present study, fibre bundles from C7 were confirmed in one animal with four plexus-forming spinal nerves and, to a very limited degree, in one additional limb; otherwise, the nerve derived exclusively from C8. In the dromedary, thoracodorsal fibre bundles arise from both C8 and T1 (Smuts and Bezuidenhout 1987b). In the dog, Sharp et al. (1991) described origins in 51.2% of cases from C7, 43.1% from C8, and a small remainder from T1.

### **Nervi pectorales craniales and caudales**

In alpacas, Goshima Watanabe (1976) attributed the origin of the pectoral nerves, without distinguishing between cranial and caudal pectoral nerves, exclusively to T1. In the present dissections, this applied only to the *n. pectoralis caudalis*, which also received a contribution from C8. By contrast, the *n. pectoralis cranialis* arose almost entirely from C8. In dromedaries, both nerves are reported to arise from C8 and T1 (Smuts and Bezuidenhout 1987b). In dogs, the composition is highly variable: the *n. pectoralis cranialis* usually arises from C6, C7, or C8, typically involving two of these roots (de Lahunta and Evans 2013), while the *n. pectoralis caudalis* consists of 3–4 branches, in 81.4% of cases arising from C8, with additional contributions from T1 and, occasionally, C7 (Sharp et al. 1991).

Overall, nerves of the brachial plexus supplying the extrinsic musculature of the forelimb arise from fewer spinal nerves than those innervating intrinsic muscles. In short-necked mammals, these nerves typically derive from two spinal roots, with C7 predominating except for the caudal pectoral nerve. In camelids with elongated necks, however, the roots forming the extrinsic muscle nerves are shifted caudally, and in alpacas, most arise primarily from C8. The *n. pectoralis caudalis*, and in rare cases the *n. thoracodorsalis*, are the only nerves that consistently receive fibre bundles from adjacent spinal nerves.

### ***Nervus suprascapularis***

In alpacas, the *n. suprascapularis* arises from the ventral branches of C7 and C8 (Goshima Watanabe 1976), as in the dromedary (Smuts and Bezuidenhout 1987b). In the dog, 65% of efferent axons derive from C6, with the remainder from C7 (Sharp et al. 1991); in rare cases, C5 may also contribute (de Lahunta and Evans 2013). Among domestic mammals and in humans, the nerve consistently originates from the cranial roots of the plexus, most commonly C6 and C7 (Reimers 1925; Seiferle and Boehme 2003). In ruminants, the suprascapular and subscapular nerves arise together from the cranial trunk of the plexus (Reimers 1925), a pattern consistent with the present observations in alpacas.

### ***Nervi subscapulares***

The *nn. subscapulares*, like the *n. suprascapularis* originates from the cranial roots of the plexus. In alpacas (Goshima Watanabe 1976), dromedaries (Smuts and Bezuidenhout 1987b), dogs (Allam et al. 1952; Sharp et al. 1991), and ruminants (Reimers 1925), its origin is identical to that of the *nn. suprascapularis*. In the horse, however, in addition to the major contribution from C7, fibre bundles also arise from C8 – an arrangement atypical for most other domestic mammals (Reimers 1925).

### ***Nervus axillaris***

In the present study, the *n. axillaris* arose from the cranial cord, composed of fibre bundles from C7

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and C8, with C8 usually predominating. Goshima Watanabe (1976) likewise described its origin from the dorsocranial cord in alpacas, but, contrary to the present findings, reported contributions from C8 and T1. His account corresponds to that in the dromedary (Smuts and Bezuidenhout 1987b). In most domestic mammals, the *n. axillaris* originates from C7 and C8, that is, from the mid to cranial portions of the plexus (Seiferle and Boehme 2003). In dogs, nearly 90% of the fibres derive from C7, with smaller contributions from C6 or C8 (Allam et al. 1952; Sharp et al. 1991). In ruminants and pigs, the origin is often slightly more cranial, arising from C6 and C7 and less frequently from C8 (Reimers 1925).

### ***Nervus radialis***

The *n. radialis* is one of the largest nerves of the forelimb in all mammals (Seiferle and Boehme 2003). Its prominence reflects its extensive distribution: it provides motor innervation to all extensors of the elbow, carpal, and digital joints, and sensory supply to the cranial forearm and dorsal digits (Seiferle and Boehme 2003; de Lahunta and Evans 2013; de Souza Junior et al. 2017). Except for the horse, the *n. radialis* in domestic mammals shares a common origin with the *nn. axillaris* and *thoracodorsalis* (Reimers 1925), corresponding to the cranial cord in alpacas.

The nerve has a relatively broad composition. In dogs, it consistently receives fibres from C7–T1, with occasional contributions from C6 or T2; C8 constitutes the largest proportion (44.6%) (Sharp et al. 1991). In alpacas, as in the dromedary, the radial nerve is formed mainly from C8 and T1, with C8 predominating (Goshima Watanabe 1976; Smuts and Bezuidenhout 1987b). This corresponds to its origin from the dorsocranial strand, equivalent to the cranial cord in the present description. Similarly, in other domestic mammals, the radial nerve derives from C7–T1, with C8 as the principal contributor (Reimers 1925; Seiferle and Boehme 2003). Thus, across the species compared, the composition of the *n. radialis* is largely consistent.

### ***Nervus musculocutaneus***

Goshima Watanabe (1976) described the *n. musculocutaneus* in alpacas as arising together with

the *n. medianus* from the ventrocaudal strand, composed of fibre bundles from C8 and T1. This arrangement is also reported in the dromedary (Smuts and Bezuidenhout 1987b). In the present study, however, the origin differed markedly: the nerve could be traced proximally, shortly after exiting the scalene gap, to the ventral branch of C7, corresponding to the caudal division of the cranial trunk. On its strictly caudal course, it crossed medially over other plexus components, received a fine communicating branch from the middle trunk, and thereby incorporated a minor C8 contribution. In domestic mammals, the *n. musculocutaneus* nerve generally arises from the cranial roots of the plexus, immediately caudal to the *n. suprascapularis*. In horses and ruminants, it is mainly composed of C6 and C7 fibre bundles, with C8 contributing in about one-third of horses (Reimers 1925; Seiferle and Boehme 2003). In dogs, the origin lies one segment more caudal, predominantly from C7 (Allam et al. 1952); Sharp et al. (1990) attributed 57% of efferent fibres to C7, although contributions may come from C6–T1 (Sharp et al. 1990). In humans, the *n. musculocutaneus* also arises from the cranial portion of the plexus, typically C5–C7 (Sirico et al. 2019).

### ***Nervus medianus***

In domestic mammals and camelids, the *n. medianus* is formed primarily from C8 and T1. In alpacas, Goshima Watanabe (1976) described its origin from the ventrocaudal strand, together with the *nn. ulnaris* and *musculocutaneus*, exclusively from C8 and T1, a pattern also reported in the dromedary (Smuts and Bezuidenhout 1987b). This was confirmed in the present study, with C8 generally contributing more strongly than T1. In dogs, the *n. medianus* likewise arises mainly from C8 and T1, but contributions from C7 and T2 are common. Sharp et al. (1990) reported constant participation of C8 and T1, with C7 present in five of six cases and T2 in four of six. Importantly, they emphasised the fibre exchange between the median and musculocutaneous nerves: before this connection, only 9% of median nerve fibres originated from C7, whereas after the communication, nearly 40% did (Sharp et al. 1990).

In ruminants and horses, Reimers (1925) described a bipartite origin: a lateral root from C7

and sometimes C8, closely associated with the *n. musculocutaneus*, and a medial root from C8 and T1. The *n. medianus* is formed only after the two portions unite in the *ansa axillaris* (Reimers 1925). In the present dissections of alpacas, fibre bundles crossing from the *n. musculocutaneus* to the *n. medianus* within the *ansa axillaris* were likewise observed, providing additional contributions from C7 and C8. Thus, in alpacas, the median nerve ultimately contains fibre bundles from all plexus-forming spinal nerves – C7, C8, and T1 – and is the only nerve of the plexus to do so.

### *Nervus ulnaris*

In domestic mammals as well as in the dromedary and alpaca, the *n. ulnaris* is formed primarily from C8 and T1. In alpacas (Goshima Watanabe 1976) and dromedaries (Smuts and Bezuidenhout 1987b), it derives exclusively from these two spinal nerves. In the present study, T1 predominated, and in some limbs the nerve consisted solely of T1 fibre bundles. In dogs, Sharp et al. (1990) found contributions from C8 and T1 in all six specimens, with T1 accounting for 65% of fibres. In four of six dogs, T2 was also involved, and in one case, C7 contributed (Sharp et al. 1990). In horses and ruminants, the *n. ulnaris* likewise arises from C8 and T1, with additional fibre bundles from T2; here too, T1 consistently represents the major component (Agduhr 1915; Reimers 1925; Seiferle and Boehme 2003).

Further findings on the topography and innervation patterns of the brachial plexus nerves in the alpaca, obtained within the same series of dissections, are currently being prepared for publication. These include variations in the distribution of fibre bundles, typically attributed to the *n. musculocutaneus*—such as contributions to the *n. cutaneus antebrachii medialis* and muscular branches to the *m. brachialis* as well as to the *m. coracobrachialis*—which were, in the present study, traced to the *n. medianus* and *n. ulnaris*.

The brachial plexus of the alpaca is primarily formed by the ventral branches of the seventh and eighth cervical and the first thoracic nerves, thus comprising mainly three spinal nerves. In a few individuals, the second thoracic nerve also contributes, though its involvement is minor and it merges proximally with the adjacent spinal branch (T1). The eighth cervical nerve consistently provides

the largest proportion of fibre bundles, while T1 plays a dominant role in the formation of the major peripheral nerves extending to the digits. This organisation is largely comparable to that of the related dromedary and members of the Giraffidae (okapi, giraffe), species that share the anatomical specialisation of an elongated neck. Compared with mammals lacking this adaptation, the alpaca exhibits a reduced number of spinal nerves participating in plexus formation, suggesting a negative allometric relationship between neck length and the number of contributing spinal nerves – that is, the longer the neck, the fewer the spinal roots forming the brachial plexus. Furthermore, the C8 and T1 roots pass through the scalenus musculature separately from C7, a configuration rarely described in other mammals. These findings provide an anatomical basis for clinical approaches to the forelimb of alpacas, particularly for neurological assessment and regional anaesthesia. In addition, the detailed description of the position and bifurcation of the interscalene space may assist in ultrasound-guided brachial plexus blocks. Overall, the present study helps close the anatomical knowledge gap in the increasingly important South American camelids and enhances the comparative understanding of the remarkable morphological diversity of the brachial plexus among mammals.

### Conflict of interest

The authors declare no conflict of interest.

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