

Brachial Plexus in the Pampas Fox (*Lycalopex gymnocercus*): a Descriptive and Comparative Analysis

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ABSTRACT

Twenty thoracic limbs of ten *Lycalopex gymnocercus* were dissected to describe origin and distribution of the nerves forming brachial plexuses. The brachial plexus resulted from the connections between the ventral branches of the last three cervical nerves (C6, C7, and C8) and first thoracic nerve (T1). These branches connected the suprascapular, subscapular, axillary, musculocutaneous, radial, median and ulnar nerves to the intrinsic musculature and connected the brachiocephalic, thoracodorsal, lateral thoracic, long thoracic, cranial pectoral and caudal pectoral nerves to the extrinsic musculature. The C7 ventral branches contribute most to the formation of the nerves (62.7%), followed by C8 (58.8%), T1 (40.0%) and C6 (24.6%). Of the 260 nerves dissected, 69.2% resulted from a combination of two or three branches, while only 30.8% originated from a single branch. The origin and innervation area of the pampas fox brachial plexus, in comparison with other domestic and wild species, were most similar to the domestic dog and wild canids from the neotropics. The results of this study can serve as a base for comparative morphofunctional analysis involving this species and development of nerve block techniques. *Anat Rec*, 300:537–548, 2017. © 2016 Wiley Periodicals, Inc.

Key words: Azarás fox; forelimb; peripheral nervous system; thoracic limb; wild carnivorans

INTRODUCTION

Lycalopex gymnocercus (G. Fischer, 1814), known as the pampas fox, Azara's fox or Azara's zorro, is a wild canid with distribution restricted to southern Brazil, eastern Argentina and Uruguay, eastern Bolivia and western Paraguay. It inhabits the Pampas biome and part of the Campos Gerais biome (Mata Atlântica domain) until the transition area with the Cerrado biome (Langguth, 1975). Its total length varies from 86.0 to 106.0 cm and its body mass is between 3 and 8 Kg. It has a thin snout, yellowish-gray fur on its back, pale underparts and furry tail. In addition, it has solitary

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and nocturnal habits and an omnivorous diet, composed of small vertebrates, insects and plants (Eisenberg and Redford, 1999; Hunter, 2011). Included in the Appendix II of CITES (CITES, 2014), it is often targeted for eradication by livestock breeders and hunted for its fur besides facing habitat destruction (Jiménez et al., 2008). Detailed studies of the anatomy of the pampas fox are limited to describing its encephalic vascularization (Depedrini and Campos, 2003; Depedrini and Campos, 2007), the topography of its lumbar intumescence and medullary conus (Souza Junior et al., 2014c) and lumbosacral plexus formation (Lorenzão et al., 2016).

Since thoracic limbs not only act in locomotion, but also serve to capture prey, analysis of their morphology can reveal good predictors of numerous ecological variables, such as the size and kind of the prey, the locomotor repertoire, the role in supporting the body mass and the habitat (Meachen-Samuels and Van-Valkenburgh, 2009). Although the study of the musculature of the limbs is adequate for a functional understanding, knowledge of the nerves that stimulate those muscles is essential for systematic studies of the physiology of locomotion (Yoshitomi et al., 2012). The brachial plexus of nerves is usually formed by a varied pattern of junctions between the ventral branches of the sixth, seventh and eighth cervical spinal nerves (C6, C7, and C8) and the first and second thoracic spinal nerves (T1 and T2) (Getty, 1986). The nerves run through the intertransversal muscles, crossing the ventral edge of the scalenus muscle and extending to the limb through the axillary space. Their fibers travel short distances and segregate into variable combinations to form the nerves that supply the muscles and skin of the thoracic limb (Evans and De Lahunta, 2013).

Comparative study of the formation of the brachial plexus between species has attracted interest since the nineteenth century (Paterson, 1887), but according to Johnson et al. (2010), its understanding remains one of the most challenging areas of contemporary anatomy. Variations in the levels of origins of the brachial plexus can be related to genetic and embryonic factors, represented by the position in which the buds of limbs develop in relation to the neural axis. According to Carpenter (1978), the more cephalic this region is, the more cranial will be the branches that participate in forming the plexus. Comparative anatomic analyses of the brachial plexus can also corroborate the hypothesis that during the evolutionary process a cranial migration occurred of the spinal nerves that take part in forming this plexus (Parada et al., 1989). From an applied standpoint, the morphofunctional study of this plexus facilitates diagnosis of neuromuscular dysfunctions and guides development of regional nerve block techniques (Johnson et al., 2010).

Despite ample morphofunctional knowledge of the brachial plexus of domestic dogs and cats (Allam et al., 1952; Sharp et al., 1990; Sharp et al., 1991; Aubert et al., 2004), descriptions containing both the origin and distribution of this plexus in wild carnivores still scarce. These are restricted to *Ursus maritimus* (Matsushima, 1966 apud Yoshitomi et al., 2012), *Arctocephalus australis* (Souza et al., 2010), *Atelocynus microtis* (Pinheiro et al., 2013), *Leopardus pardalis* (Chagas et al., 2014) and *Cerdocyon thous* (Souza Junior et al., 2014b) and most of these studies are based on dissection of only one or two individuals.

Because of this lack of anatomical knowledge, the aim of this study was to describe the origin and ramifications of the brachial plexus of *L. gymnocercus*. Thus, the results can be useful for veterinary procedures in the species, as well as provide a base for studies of functional aspects, evolutionary biology and zoology.

MATERIALS AND METHODS

We analyzed the thoracic limbs and respective brachial plexuses of ten adult specimens of *Lycalopex gymnocercus* (seven males and three females) found dead on highways in the southwestern part of the state of Rio Grande do Sul, Brazil. The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) approved the study (IBAMA/SISBIO authorization no. 33667-1). The cadavers were transported to the Laboratory of Animal Anatomy of Federal University of Pampa (UNIPAMPA), Uruguaiana, Rio Grande do Sul, Brazil, where they were fixed with subcutaneous, intramuscular and intracavity injection of an aqueous solution of 50% buffered formaldehyde and then immersed in a low-density polyethylene plastic box containing the same solution at 10% for at least 14 days before dissection.

Macroscopic dissections were carried out to reveal the muscles and the origins and ramifications of the nerves forming the brachial plexus. After complete removal of the skin and fasciae, we made two sagittal incisions in the pectoral musculature, extending from the manubrium to the xyphoid levels, followed by abduction of the limbs to provide more axillary space for dissection of the nerves. The axillary and brachial vessels' arrangement were recorded in relation to the nerves and then they were removed. For better visualization of the cervical and thoracic ventral branches, we removed the musculature that covered the intervertebral foramina and vertebral bodies with tweezers and a Farabeuf chisel (10 mm). The transverse processes were removed with pliers and the spinal medulla was exposed ventrally by abrasion of the vertebral bodies with a pear-tipped vulcanite drill bit coupled to a power drill (Black & Decker, 9.6V®). The nerves formations were determined carefully after epineurium removal. The nerves were denominated in conformity with *Nomina Anatomica Veterinaria* (2012), except for the brachiocephalic nerve, which was designated according to Evans and De Lahunta (2013).

Finally, we took photos with a digital camera (Canon® EOS Rebel T3i, 16MP) and made schematic drawings of all the plexuses. The data containing the origins of each nerve were tabulated in spreadsheets and t-tests were performed for comparison of the mean numbers of branches forming the plexuses between antimers and sexes, at 5% significance, with the BioEstat 5.3® software.

RESULTS

The macrodissections allowed systematizing and documenting the components of the brachial plexus in the 10 *Lycalopex gymnocercus* specimens. The 20 plexuses resulted from the connections between the ventral branches of the last three cervical spinal nerves (C6, C7, and C8) and the first thoracic spinal nerve (T1). These branches connected the suprascapular, subscapular,

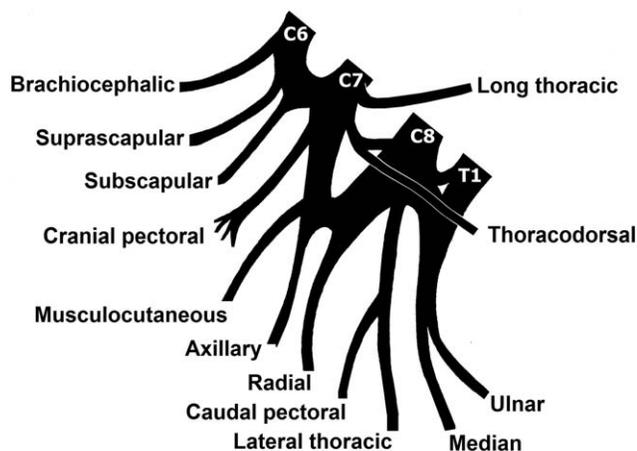


Fig. 1. Diagram of the most common origin and distribution of the nerves of the brachial plexus of *Lycalopex gymnocercus*.

axillary, musculocutaneous, radial, median and ulnar nerves to the intrinsic musculature and connected the brachiocephalic, thoracodorsal, lateral thoracic, long thoracic, cranial pectoral and caudal pectoral nerves to the extrinsic musculature (Figs. 1 and 2). The phrenic nerve, although not part of the plexus, started from C7 in all the plexuses.

When considering the set of 13 nerves dissected in the 20 plexuses ($n = 260$), we found that the ventral branches of C7 contributed most to the nerve formation (62.7%), followed by C8 (58.8%), T1 (40.0%) and C6 (24.6%). The sum of the number of ventral branch contributions to form the 20 plexuses did not differ between antimers: there were exactly 242 in each side (Fig. 3). All told, 484 ventral branches formed 260 nerves and each nerve was formed, on average, by a combination of nearly two branches (1.86 branches/nerve). With respect to the sexes, each nerve was formed by an average of 1.86 branches in both males and females. There was no significant difference ($\alpha = 0.05$) between the number of contributions of the branches between the sexes (P -value = 0.9651) or antimers (P -value = 1.00).

The origin of the nerves was exactly symmetrical in two male individuals (20%). The differences found in the origin of the nerves between the right and left plexuses of a single individual were restricted to at most three different branch contributions.

The origin of each nerve and its motor innervation are shown in Tables 1 and 2.

The suprascapular nerve entered in the groove between the supraspinatus and subscapularis muscles, accompanied by suprascapular vessels. The nerve crossed to the lateral surface, innervated the supraspinatus muscle and passed ventral to the acromium to reach infraspinatus muscle. The subscapular was a single and short nerve that became divided in two branches to innervate the subscapular muscle and ended restricted to the medial face of the limb.

The axillary nerve was proximally accompanied by axillary artery and entered the space between subscapular and teres major muscles. At this level, it divided into a short part to supply subscapular and teres major muscles and a long part that crossed to the lateral surface of the limb to innervate both parts of deltoideus and

teres minor muscle. This last part followed distally, parallel to caudal circumflex humeral artery and axillobrachial vein, and originated the cranial lateral cutaneous nerve. This nerve ran distally accompanied by the cephalic vein and, at the level of flexor surface of the elbow, anastomosed with a superficial branch from radial nerve. From this point, it followed distally to the forearm and became the cranial cutaneous antebrachial nerve.

The musculocutaneous nerve ran close to the caudal margin of biceps brachii muscle and offered a small branch to the coracobrachialis muscle, a large proximal branch to the biceps brachii and a distal branch to the brachial muscle. A communicating branch to the median nerve emerged just proximal to the distal branch to the brachial muscle. The distal continuation of musculocutaneous nerve was the medial cutaneous antebrachial nerve, which passed over pronator teres muscle and ended at the level of distal radius.

The radial was the largest nerve and innervated more muscles than any other. It passed between the axillary vessels and crossed from medial to lateral surface in the space between long and medial heads of triceps brachii muscle. In this pathway, the radial nerve gave branches to tensor fascia antebrachial muscle and to all heads of triceps brachii muscle. Distally the nerve followed on the lateral surface of brachial muscle and divided into two main branches: deep and superficial. The deep distributed branches to all craniolateral muscles of the forearm and ended at the level of distal radius. The superficial branch was cutaneous and ran cranially in the forearm. It divided into lateral and medial parts at the level of the third of the radius. Both parts followed distally, parallel to the cephalic vein, and ended on the dorsal surface of the paw. The medial branch joined the cranial lateral cutaneous brachial nerve.

The median and ulnar nerves arose together and enveloped by a delicate fascia. The median diverged from ulnar nerve at the level of proximal humerus but didn't give off branches until it reached the medial epicondyle. The muscular branches of the median nerve supplied all of the caudomedial muscles of the forearm, excepting flexor carpi ulnaris. Finally, the nerve followed distally in the forearm accompanied by the median vessels and finished in the palmar surface of the paw.

The ulnar nerve was the most caudally located nerve of the plexus in the arm. This nerve followed along with the medial head of the triceps brachii muscle, crossed caudally to the medial epicondyle and deepened under the ulnar head of the flexor carpi ulnaris. It gave off muscular branches to both heads of flexor carpi ulnaris and to the humeral head of the deep digital flexor. Proximally in the arm the ulnar nerve originated the caudal cutaneous antebrachial nerve directed to the olecranon region. At the level of the middle third of the forearm, the ulna nerve originated a palmar and a dorsal branch that ended in the palmar surface of the paw.

The brachiocephalic nerve passed cranially to the shoulder joint, supplied cleidobrachialis muscle and continued as a cutaneous nerve to the cranial part of the arm. Among the nerves that supplied the extrinsic musculature, only the brachiocephalic originated a cutaneous branch. The cranial and caudal pectoral nerves had a short path until reached the corresponding pectorales muscles. The long thoracic nerve passed on the lateral

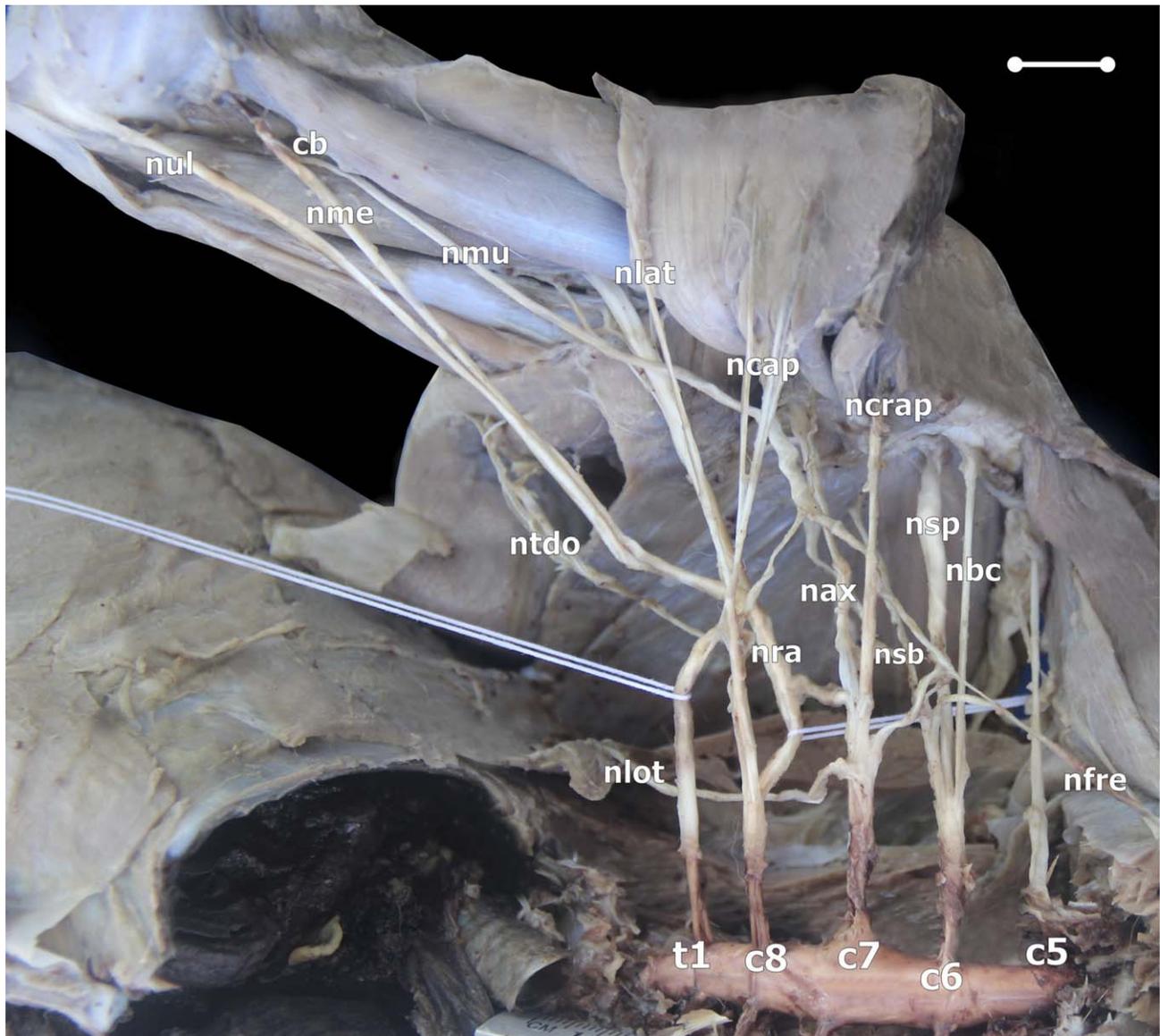


Fig. 2. Origin and ramification of the right brachial plexus of an adult male *Lycalopex gymnocercus* (ventromedial view). **c5**, **c6**, **c7**, **c8**, cervical segments 5, 6, 7 and 8; **t1**, thoracic segment 1; **nbc**, brachiocephalic nerve; **nax**, axillary nerve; **ncrap**, cranial pectoral nerves; **ncap**, caudal pectoral nerves; **nme**, median nerve; **nra**, radial nerve; **nsb**,

subscapular nerve; **nsp**, suprascapular nerve; **ntdo**, thoracodorsal nerve; **nlot**, long thoracic nerve; **nlat**, lateral thoracic nerve; **nmu**, musculocutaneous nerve; **nul**, ulnar nerve; **cb**, communicating branch between musculocutaneous and median nerves; **nfre**, phrenic nerve (cranially folded). Scale bar 1cm.

surface of the thoracic part of the serratus ventralis muscle to supply it. The thoracodorsal nerve accompanied the thoracodorsal vessels deep to the latissimus dorsi muscle. The thoracic lateral nerve followed together with the thoracic lateralis vessels, dorsally to the dorsal margin of deep pectorales and medially to axillary lymph nodes.

The axillary artery was situated caudally to the musculocutaneous nerve, medially to the radial nerve and cranially to the common trunk of the median and ulnar nerves. The brachial artery was located just caudal to musculocutaneous nerve and cranially to the median and ulnar nerves. The median artery followed the

median nerve along its course in the antebrachium, both deeply protected by forearm muscle.

DISCUSSION

Origin of the Brachial Plexus

The brachial plexus of *Lycalopex gymnocercus* started from the ventral spinal branches C6, C7, C8 and T1 in the 20 limbs analyzed. This coincides with the most frequent formation (58.62%) of the plexuses of domestic dogs, although the contribution of C5 and/or T2 was also observed by Allam et al. (1952). This formation of the brachial plexus has also been confirmed in the other

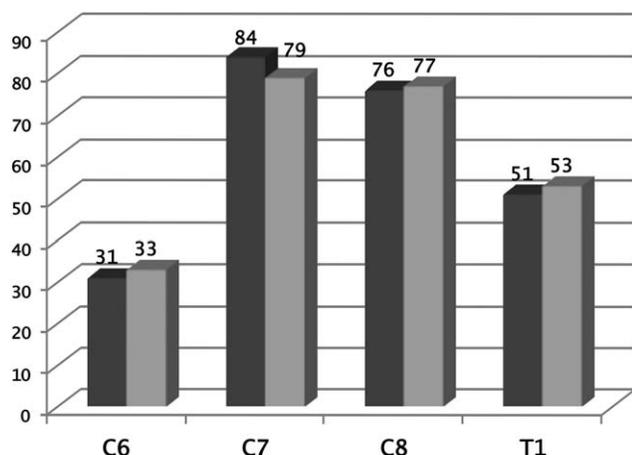


Fig. 3. Graph representing the total number of contributions of the ventral branches (segments C6, C7, C8 and T1) between antimers in the formation of the brachial plexuses ($n = 20$) of *Lycalopex gymnocercus* (left limb: dark grey columns; right limb: light grey columns).

carnivores for which the brachial plexus has been described: domestic cats (Getty, 1986; Aubert et al., 2004), *Arctocephalus australis* (Souza et al., 2010), *Atelocynus microtis* (Pinheiro et al., 2013), *Cerdocyon thous* (Souza Junior et al., 2014b) and *Leopardus pardalis* (Chagas et al., 2014) and. Without specifying the species, Paterson (1887) reported that in “foxes” only four branches form the brachial plexus, without mentioning which ones, but we assume they are the same ones found in *L. gymnocercus* since C6, C7, C8 and T1 form the plexus in all mammals studied so far. Non-carnivorous species having similar origin of the plexus are: *Connochaetes sp.*, *Camelus sp.*, *Coendou prehensilis*

(Paterson, 1887), sheep and goats (Getty, 1986), *Capri-cornis crispus* (Atoji et al., 1987), *Chinchilla lanigera* (Gamba et al., 2007), *Mazama gouazoubira* (Melo et al., 2007; Vieira et al., 2013) and *Okapia johnstoni* (Endo et al., 2009).

According to Allam et al. (1952), this configuration of the brachial plexus, practically confined to four ventral spinal branches, is associated with a certain limitation of movements accompanied by an absence of a clavicle and by concomitant adaptive simplifications of the shoulder muscles. Species that use forelimbs for climbing, digging, running, swimming and grappling or handling preys or food tend to have the brachial plexus formed usually by five or usually six or even more ventral branches. This is the case of the primates *Presbytis hoseyi*, *Cebus capucinus* (Paterson, 1887), *Cebus apella* (Ribeiro et al., 2005), *Papio ursinus* (Booth et al., 1997), *Pongo pygmaeus* (Kawashima et al., 2006), *Lagothrix lagothricha* (Cruz and Adami, 2010) and humans (Uysal et al., 2003). Other species that exhibit a varied repertoire of movements in the forelimbs, like the monotremes (Koizumi and Sakai, 1997), *Myocastor coypus* (Pop et al., 1997), *Bradypus variegatus* (Amorim Junior et al., 2003), *Hydrochaeris hydrochaeris* (Fioretto et al., 2003), *Agouti paca* (Scavone et al., 2008), *Tamandua tetradactyla* (Cruz et al., 2012) and *Myrmecophaga tridactyla* (Souza et al., 2014), also have five or more ventral branches forming brachial plexus.

By contrast, species that use the forelimbs essentially to support the weight and to walk (cursorials) exhibit four ventral branches with an eventual minor contribution of a fifth branch. This occurs in most of the ungulates as the case of domestic herbivores (Magilton et al., 1968) and wild ruminants like the *Capricornis crispus* (Atoji et al., 1987) and *Mazama gouazoubira* (Vieira et al., 2013).

TABLE 1. Origin and frequency of the nerves of the brachial plexus that supply the intrinsic muscles of the thoracic limb ($n = 20$) of *Lycalopex gymnocercus*

Nerves	Origin	Frequency	%	Innervated muscle
<i>Suprascapularis</i>	C6	4	20	<i>Supraspinatus</i> and <i>infraspinatus</i> .
	C6 e C7	15	75	
	C7 e C8	1	5	
<i>Subscapularis</i>	C6 e C7	18	90	<i>Subscapularis</i> .
	C7	1	5	
	C7 e C8	1	5	
<i>Musculocutaneus</i>	C6 e C7	4	20	<i>Coracobrachialis</i> , <i>biceps brachii</i> and <i>brachialis</i> .
	C6, C7 e C8	1	5	
	C7	6	30	
	C7 e C8	8	40	
	C7, C8 e T1	1	5	
<i>Axillary</i>	C6, C7 e C8	2	10	<i>Subscapularis</i> , <i>teres major</i> , <i>teres minor</i> and <i>deltoideus</i> (<i>pars acromialis</i> and <i>scapularis</i>).
	C7	6	30	
	C7 e C8	12	60	
<i>Radial</i>	C7 e C8	2	10	<i>Tensor fasciae antebrachii</i> , <i>triceps brachialis</i> , <i>anconeus</i> and <i>craniolateral forearm muscles</i> .
	C7, C8 e T1	14	70	
	C8 e T1	4	20	
<i>Median</i>	C7 e C8	2	10	<i>Pronator teres</i> , <i>flexor carpi radialis</i> , <i>flexor digitorum profundus</i> , <i>flexor digitorum superficialis</i> and <i>pronator quadratus</i> .
	C7, C8 e T1	2	10	
	C8 e T1	14	70	
	T1	2	10	
<i>Ulnar</i>	C7 e C8	2	10	<i>Flexor carpi ulnaris</i> and <i>flexor digitorum profundus</i> .
	C7, C8 e T1	2	10	
	C8 e T1	14	70	
	T1	2	10	

TABLE 2. Origin and frequency of the nerves of the brachial plexus that supply the extrinsic muscles of the thoracic limb ($n = 20$) of *Lycalopex gymnocercus*

Nerves	Origin	Frequency	%	Innervated muscle
<i>Brachiocephalic</i>	C6	20	100	<i>Clidobrachialis</i>
<i>Long thoracic</i>	C7	20	100	<i>Serratus ventralis thoracis</i>
<i>Thoracodorsal</i>	C7 e C8	10	50	<i>Latissimus dorsi</i>
	C7, C8 e T1	4	20	
	C8	1	5	
	C8 e T1	5	25	
<i>Lateral thoracic</i>	C7, C8 e T1	7	35	<i>Pectorales profundus and cutaneous trunci</i>
	C8	2	10	
	C8 e T1	9	45	
	T1	2	10	
<i>Cranial pectoral</i>	C6 e C7	1	5	<i>Pectorales superficiales</i>
	C7	8	40	
	C7 e C8	4	20	
	C7, C8 e T1	2	10	
	C8	2	10	
	C8 e T1	3	15	
<i>Caudal pectoral</i>	C7, C8 e T1	7	35	<i>Pectorales profundus</i>
	C8	2	10	
	C8 e T1	9	45	
	T1	2	10	

Although the C7 ventral branch, alone or in combination, predominated as the origin of the majority of nerves in all the plexuses analyzed (62.7%), its contribution was greater for nerves that supply extrinsic muscles, whose motor importance is less. The C8 branch was present in the formation of 58.8% of the nerves, especially those running to the intrinsic muscles. Therefore, lesions in C8 can have greater functional repercussion. When considering the possible combinations between branches, those between C8 and T1 were the most common in forming the nerves in all the plexuses (22.3%), predominantly to intrinsic muscles.

The most cranial point of origin of the brachial plexuses of *L. gymnocercus* was the C6 ventral branch in all the individuals dissected. According to Parada et al. (1989), during the evolutionary process, the origin of this plexus ascended in the cranial direction, reaching the fourth cervical spinal nerve in some apes and the third in humans. However, the presence of C4 in the formation of the plexus of monotremes (Koizumi and Sakai, 1997), sloths (Amorim Júnior et al., 2003), capybaras (Fioretto et al., 2003) and collared peccary (Moura et al., 2007) shows that the origin in the most cranial branches is not characteristic of more recent species. The genus *Lycalopex* arose more recently on the evolutionary scale than did many of these species, but the origin of the plexus is in a more caudal segment. These results are in line with those reported by Carpenter (1978) and Moura et al. (2007), who suggest that changes in the origin of the plexus are due to variations in the insertion position of the buds of the limbs in relation to the neural axis.

Of the total of 260 nerves whose origin we studied, 69.2% started from a combination of two or three ventral spinal branches, while only 30.8% came from a single branch. Of the 140 nerves that supply the intrinsic muscles, 84.2% had more than one origin, suggesting greater complexity and functional relevance of these nerves. The important radial nerve, which supplies the large majority of the extensor muscles, always originated from a combination of two (30%) or three branches (70%).

Although all the *L. gymnocercus* plexuses derived from C6, C7, C8 and T1, there were some variations in the formation of each nerve, including between antimers of the same animal, as also verified in the capybara by Fioretto et al. (2003). According to Johnson et al. (2010), variations in the neural architecture of the brachial plexus are more the rule than an exception. In a study of 200 plexuses of human fetuses, Uysal et al. (2003) observed that only 46.5% had an organization considered typical, while the majority (53.5%) had some significant variation in relation to the expected pattern. After analyzing 100 brachial plexus of human cadavers, Malukar and Rathva (2011) reported a high incidence of variations, including absence of nerves and bilateral variation.

Variations in the patterns of origin and ramification of brachial plexus can be explained through neuronal growth cones behaviors during embryonic development. Alterations in signaling between mesenchymal cells and neuronal growth cones can lead to significant variations that would persist postnatally (Dent et al., 2003).

Among 25 published studies of the anatomy of the brachial plexus of wild species, in more than half the authors did not employ more than five specimens (Pateron, 1887; Wakuri and Kano, 1966; Koizumi and Sakai, 1997; Aydin, 2003; Fioretto et al., 2003; Cruz and Adami, 2010; Souza et al., 2010; Kikuchi et al., 2011; Cruvinel et al., 2012; Cruz et al., 2012; Yoshitomi et al., 2012; Pinheiro et al., 2013; Prestes et al., 2013; Vieira et al., 2013). Therefore, such variations might not have been noted in various reports. However, we believe the sample of 10 cadavers used in this study is sufficient to reveal the existence of variations, and because we only used roadkill cadavers, the specimens reflect the characteristics of typical individuals in the wild without any bias introduced by captivity.

Although the sample was mainly composed of males (70%), we did not observe differences in the number or complexity of the plexuses between the sexes. Nevertheless, a more sex-balanced sample might have elucidated this aspect better. Melo et al. (2007) reported that the

origin of the brachial plexus of the gray brocket deer (*Mazama gouazoubira*) is more cranial and the distribution is more complex in males than females.

The authors of primate studies have conjectured that the brachial plexus can vary in the pattern of ramifications depending on its position in relation to the axillary artery (Kikuchi et al., 2011). The axillary artery was located between the continuations of the ventral branches of C7 and C8, which coincides with that described for the majority of primates, including human beings (Johnson et al., 2010; Kikuchi et al., 2011) and with the descriptions of domestic dogs (Allam et al., 1952).

The anatomical relationships of the thoracic limb bones and vessels with the nerves of the brachial plexus in *L. gymnocercus* were very similar to the domestic dog. Thus, it is reasonable to suggest that the same anatomical landmarks and techniques for needle placement during brachial plexus anesthetic block in dogs (Futema et al., 2002; Campoy et al., 2008; Mahler and Adogwa, 2008) may also be effective in pampas fox. For the same reasons, ultrasound-guided needle insertion, as performed in dogs (Campoy et al., 2010), might also improve the rate of success of anesthetic block in pampas fox. However, electrophysiological and pharmacological studies would provide even more support.

In the brachial plexus of domestic animals, the ventral branches ramify into roots, some of which join to form the trunks of the plexus. In opposition, the brachial plexus of human and non-human primates (Cruz and Adami, 2010; Johnson et al., 2010; Kikuchi et al., 2011), as well as monotremes (Koizumi and Sakai, 1997), *Hystrix cristata* (Aydin, 2003), *Sciurus vulgaris* (Aydin, 2011), *Hippopotamus amphibius* (Yoshitomi et al., 2012), *Tamandua tetradactyla* (Cruz et al., 2012) and *Bradypus torquatus* (Cruz et al., 2013), typically demonstrate trunk arrangements: superior or cranial, middle, and inferior or caudal portions, with each trunk grossly representing the union of the cervical nerves, C5 and C6, C7, C8 and T1, respectively. More than two divisions start from each trunk, a ventral division and a dorsal division, which join to constitute cords: dorsal, lateral, and medial. In contrast, only Allam et al. (1952), in dogs, reported the existence of cord formation (superior, middle, and inferior) interposed with the roots and nerves destined to the musculature, although in this case, trunks were not observed. In the pampas fox, however, there is only one trunk, which involves the median and ulnar nerves. The construction of the plexus in trunks and cords, however, does not constitute a morphological pattern. Instead, a distinct and well-defined root arrangement predominates, similar to that found in domestic mammals.

Distribution of the Nerves to the Intrinsic Musculature

From a grouped mode it can be verified that among the nerves that supply the intrinsic musculature of the thoracic limb of *L. gymnocercus*, those whose innervation areas terminate at the proximate level of the humeral-radial-ulnar joint (suprascapular, subscapular, axillary and musculocutaneous) originate from the more cranial branches of the plexus, i.e., C6, C7, and less commonly C8. The others (radial, median and ulnar), which

continue to the distal regions of the limb to supply extensor and flexor muscles of the carpus and digits, come mainly from C8 and T1, with occasional contributions from C7. Besides this, the nerves with proximally restricted location originated in several cases from a single branch, which practically did not occur in those following a distally longer path.

Suprascapular nerve. With predominant origin at C6 and C7 (75%) in *L. gymnocercus*, the suprascapular nerve was formed similarly to the nerve in domestic dogs (Allam et al., 1952; Getty, 1986), *Arctocephalus australis* (Souza et al., 2010), *Atelocynus microtis* (Pinheiro et al., 2013) and *Cerdocyon thous* (Souza Junior et al., 2014b). An electrophysiological study of six domestic dogs revealed that the suprascapular nerve received evoked potentials from the ventral branches of C6 and C7 in all the animals evaluated (Sharp et al., 1991). This reinforces the functional importance of these branches for this nerve in canids. The origin only at C6 (20%) occurs in domestic cats (Getty, 1986) and *Leopardus pardalis* (Chagas et al., 2014). In the pampas foxes studied here, formation by C7 and C8 (5%) occurred in only one limb, something that has not been reported in other species.

Fioretto et al. (2003) suggest that the ample origin of the suprascapular nerve in some species results from the need for intense and coordinated movement of the scapular musculature during swimming. It can thus be assumed that this musculature for swimming is less functional in canids, resulting in the origin of this nerve in only one or two ventral branches, as found in *L. gymnocercus* and other canids. Contrary to this hypothesis, *A. australis* is a carnivore with thoracic limbs adapted for swimming in which the suprascapular nerve is formed by the same two branches mentioned for those canids.

With respect to the pathway and supply to the supraspinal and infraspinous muscles, the arrangement was similar to that of the domestic dog (Allam et al., 1952; Getty, 1986; Evans and De Lahunta, 2013), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). In *A. australis* (Souza et al., 2010) the nerve only innervates the subscapular and supraspinal muscles.

Subscapular nerve. The subscapular nerve had three distinct origins, the most common being from C6 and C7 (90%). This is in line with the dissections reported by Allam et al. (1952) and Getty (1986) as well as the electrophysiological studies of Sharp et al. (1991) for domestic dogs. Among carnivores, this same origin has been reported to predominate in domestic cats (Getty, 1986), *L. pardalis* (Chagas et al., 2014) *C. thous* (Souza Junior et al., 2014b). In one plexus, the nerve originated exclusively from C7, which has also been reported in *A. australis* (Souza et al., 2010). In the canid *A. microtis* it was found to originate only from C6 (Pinheiro et al., 2013). In one *L. gymnocercus* plexus, we observed the formation of the subscapular nerve by the combination of C7 with small contribution from C8 (5%), something absent in the descriptions of other species. Its pathway as a single nerve on the medial face of the subscapular muscle with distal ramification to supply this

muscle was similar to that described by Allam et al. (1952) and by Evans and De Lahunta (2013) in domestic dogs, by Pinheiro et al. (2013) in *A. microtis* and by Souza Junior et al. (2014b) in *C. thous*.

Axillary nerve. Even though C7 was identified as the origin of the axillary nerve in all the *L. gymnocercus* plexuses dissected, we noted three formation patterns of this nerve, with the combination of C7 and C8 being predominant (60%), as also observed in the *Canis familiaris* (Getty, 1986; Evans and De Lahunta, 2013), *A. australis* (Souza et al., 2010) and *C. thous* (Souza Junior et al., 2014b). The second most common origin of the axillary nerve in *L. gymnocercus* was C7 alone (30%), as also found in dogs by Allam et al. (1952). In *L. pardalis* and *A. microtis* the axillary was found to come from C6 and C7 (Chagas et al., 2014; Pinheiro et al., 2013). The axillary nerve of one female pampas fox started from branches C6, C7 and C8, something that has not been reported for any other carnivore species. Its innervation pattern is similar to that reported for domestic dogs by Getty (1986) and Evans and De Lahunta (2013), for *A. microtis* by Pinheiro et al. (2013), for domestic cats, *Puma concolor* and *Panthera onca* by Sánchez et al. (2013) and for *C. thous* by Souza Junior et al. (2014b). In *A. australis*, it supplies the subscapular, teres major and deltoid muscles (Souza et al., 2010). The rest of its fine ramifications in *L. gymnocercus* were cutaneous.

The axillary nerve originated the cranial lateral cutaneous brachial nerve, which distally continued as a cranial lateral cutaneous antebrachial nerve, similar to that reported by Getty (1986) and Evans and De Lahunta (2013) in the domestic dog and by Sánchez et al. (2013) in the domestic cat, *P. concolor* and *Panthera onca*. The anastomosis of the cranial lateral cutaneous brachial nerve with the medial division of superficial branch of the radial nerve was also recognized in *L. gymnocercus* similar to that described in Carnivores (Arlamowska-Palider, 1970).

Musculocutaneous nerve. Although irregular in its formation, the musculocutaneous nerve of *L. gymnocercus* always started at branch C7, usually with contributions from C6 and C8, which coincides with the description for domestic cats by Getty (1986) and dogs by Getty (1986) and Evans and De Lahunta (2013). The electrophysiological studies of Sharp et al. (1990) of domestic dogs confirm the importance of C7 for the musculocutaneous nerve, by concluding that most of the evoked potential to the nerve comes from this branch. The most common origin of this nerve in *L. gymnocercus* was C7 combined with C8 (40%), similar to the pattern reported for cats (Getty, 1986). Origin solely from C7 was the second most common pattern (30%), as also reported for dogs by Allam et al. (1952). In 20% of the plexuses the musculocutaneous nerve started from C6 and C7, as also described for the carnivores *L. pardalis* (Chagas et al., 2014), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). In *A. australis*, its origin is more caudal, including contribution from T1 (Souza et al., 2010). Branch T1 contributed to the musculocutaneous nerve in only one (5%) *L. gymnocercus* plexus, in combination with C7 and C8. This

shows the ample variation regarding the nerve's origin among species.

The innervation territory exhibited an arrangement similar to that of the carnivores *Canis familiaris* (Evans and De Lahunta, 2013), *Felis catus*, *Puma concolor* (Sánchez et al., 2013), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). The proximal muscular branch in *L. gymnocercus* supplied the brachial biceps muscle, as also reported for the domestic dog (Allam et al., 1952; Getty, 1986), *A. australis* (Souza et al., 2010) and *C. thous* (Souza Junior et al., 2014b). In domestic cats (Getty, 1986) the proximal branch also supplies the coracobrachialis muscle. The distal branch in *L. gymnocercus* innervated only the brachial muscle, as also reported for dogs (Allam et al., 1952). In *A. australis* (Souza et al., 2010), this branch also innervates the brachial biceps muscle.

The communicating branch between the musculocutaneous and median nerves was present in all the *L. gymnocercus* plexuses, as also observed in the domestic dog (Allam et al., 1952) and *C. thous* (Souza Junior et al., 2014b). This might be functionally important, because it may permit continuing transmission of stimuli even after injury to one of these nerves (Sharp et al., 1990). This communicating branch also carries efferent fibers from musculocutaneous to median nerve to supply the paw (Kitchell et al., 1980). In humans, the presence of a communicating branch between these nerves is regarded as one of the most common variations of brachial plexus (El Falougy et al., 2013). The studies of this specific variation in humans alerted for unusual clinical signs and caution during surgical approaches (Arques, 2015), mentioned ontogenetic and developmental aspects (Saeed and Rufai, 2003), claimed for comparative studies in mammals (Iwamoto et al., 1990), but didn't speculate functional advantages.

The musculocutaneous nerve continued distally in the forearm as a medial cutaneous antebrachial nerve, with a cutaneous area that comprised the craniomedial surface of the forearm, just as described in the domestic dog (Evans and De Lahunta, 2013), domestic cat and *P. concolor* (Sánchez et al., 2013)

Radial nerve. The radial nerve, the largest of all those composing the plexus, was formed predominantly by branches C7, C8 and T1 (70%) in *L. gymnocercus*, as is also the case in the carnivores *Canis familiaris* (Allam et al., 1952; Getty 1986; Evans and De Lahunta, 2013), *Felis catus* (Guimarães et al., 2007), *A. australis* (Souza et al., 2010) and *C. thous* (Souza Junior et al., 2014b). The C8 branch was present in the formation of all 20 radial nerves in the *L. gymnocercus* specimens dissected. This is coherent with the observations of Sharp et al. (1991) in domestic dogs, where C8 made the largest contribution in tests of evoked potential to this nerve, as well as with studies of the formation of this nerve in other domesticated and wild species. In the canid *A. microtis* (Pinheiro et al., 2013), the radial nerve was reported to come from C7 and C8, as was the case in 10% of the pampas fox plexuses. Origin from C8 and T1 (20% here) has not been reported in any other carnivore species, except from 20% of *C. thous* specimens analyzed by Souza Junior et al. (2014b). The fact that the radial nerve occurred formed by three different roots in 70% of

the *L. gymnocercus* plexuses is related to its motor importance, since its branches innervate all the extensor muscles of the elbow, carpus and digits, besides the supinator and long abductor muscles of the first digit. Therefore, the innervation area of its branches was similar for dogs (Getty, 1986; Evans and De Lahunta, 2013), *A. australis* (Souza et al., 2010), domestic cats, *P. concolor*, *P. onca* (Sánchez et al., 2013) and *C. thous* (Souza Junior et al., 2014b). The radial nerve originated a well developed (superficial) cutaneous branch, typically found in lower placental animals (Arlamowska-Palider, 1970).

Both lateral and medial branches of the superficial branch of the radial nerve provided the cutaneous innervation of craniolateral and craniomedial surfaces of the forearm and dorsal surface of the paw in the *L. gymnocercus*, as described in the domestic dog (Evans and De Lahunta, 2013), domestic cat (Guimarães et al., 2007), *P. concolor* and *P. onca* (Sánchez et al., 2013). However, the caudal lateral cutaneous brachial and the lateral cutaneous antebrachial nerves, described in the domestic cats (Getty, 1986) and dogs (Evans and De Lahunta, 2013), were not recognized in the pampas fox.

Median and ulnar nerves. The median and ulnar nerves originated together in a single trunk, predominantly formed by branches C8 and T1 (70%), which is in agreement with the electrophysiological findings of Sharp et al. (1990), who reported that the main part of the evoked potential to these nerves in dogs also came from C8 and T1. The existence of a common trunk for the ulnar and median nerves has been described in domestic carnivores (Getty, 1986), *A. australis* (Souza et al., 2010) and *C. thous* (Souza Junior et al., 2014b) without the participation of the musculocutaneous and cranial pectoral nerves.

The median nerve of *L. gymnocercus* has the same origin and distribution as described for domestic dogs by Getty (1986) and Evans and De Lahunta (2013), although Allam et al. (1952) did not mention any contribution of C7, but of T2 instead, in some of the 58 plexuses dissected. Comparatively, the median nerve has been reported to start from C8 and T1 in *A. australis* (Souza et al., 2010). The contribution of C7, C8 and T1, found in only 10% of the *L. gymnocercus* plexuses, has also been described domestic cats (Getty, 1986), *L. pardalis* (Chagas et al., 2014) and *A. microtis* (Pinheiro et al., 2013). The median nerve distribution to muscles is similar to domestic dogs (Allam et al., 1952), cats (Sánchez et al., 2013) and *C. thous* (Souza Junior et al., 2014b). In *A. australis* (Souza et al., 2010), the median nerve was found to be responsible for innervation of the pronator quadratus, pronator teres, flexor carpi radialis and both superficial and deep digital flexors muscles.

For the dog ulnar nerve, there is a slight divergence between the descriptions of Allam et al. (1952) and Getty (1986), with the latter mentioning a contribution of C7, something also found in 20% of the pampas fox plexuses. Allam et al. (1952) mentioned that the median and ulnar nerves of 29 dogs came only from C8 and T1, with occasional contribution from T2. In the dissections performed, T2 did not contribute to any nerve. Sharp et al. (1990) also observed that C8 and T1 participated in the formation of the ulnar nerve in all six dogs analyzed, while C7 contributed in only one individual and gave

rise to only 1% of the efferent fibers to this nerve, going to the ulnar flexor of the carpus muscle. In *L. gymnocercus*, the median and ulnar traveled in a common trunk to the middle third of the medial face of the arm, from where the ulnar nerve continued along a more caudal path to the medial epicondyle of the humerus to innervate portions of the deep flexor muscles of the digits and the ulnar flexor of the carpus. The pathway and distribution area of this nerve are identical to those described by Allam et al. (1952) and Evans and De Lahunta (2013) in domestic dogs, in *A. australis* (Souza et al., 2010) and *C. thous* (Souza Junior et al., 2014b). The majority origin of the ulnar nerve in C8 and T1 (70%) has also been reported in carnivores like domestic cats (Getty, 1986), *L. pardalis* (Chagas et al., 2014), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). Origin from C7 and C8, which occurred in 10% of the pampas fox plexuses, was not described in the carnivores studied. In *A. australis* (Souza et al., 2010), the origin was from C8, T1 and T2.

The cutaneous nerves originated by median and ulnar nerves provided cutaneous innervation to caudal surface of the forearm and palmar surface of the paw in the *L. gymnocercus* as described for the domestic dog (Getty, 1986; Evans and De Lahunta, 2013).

Distribution of the Nerves to the Extrinsic Musculature

These nerves originated in ample and diversified form from roots C7 to T1. The C6 branch formed the brachiocephalic nerve in all the limbs but contributed to the formation of the cranial pectoral nerve in only one limb. According to Fioretto et al. (2003), the extensive origin of these nerves reflects their ample innervation areas, since the extrinsic musculature reaches regions more distant from the limb.

Brachiocephalic nerve. The brachiocephalic nerve came from C6 in all the *L. gymnocercus* plexuses and showed a path and innervation area in the cleidobrachial muscle similar to that described for dogs (Evans and De Lahunta, 2013) and *C. thous* (Souza Junior et al., 2014b). Although anatomical and electrophysiological studies often mention the contribution of C7 in forming this nerve in dogs, C6 is indicated as its main branch (Allam et al., 1952; Sharp et al., 1991). While it is not listed in *Nomina Anatomica Veterinaria* (2012), we agree with authors who have described in the plexus of dogs (Allam et al., 1952; Sharp et al., 1991; Evans and De Lahunta, 2013) because of its origin at C6 and the fact it supplies an important extrinsic muscle of the limb. Thus, morphologically it participates in the brachial plexus. In *L. gymnocercus*, along with the long thoracic nerve it was a nerve with constant formation. As in the dog (Evans and De Lahunta, 2013), the brachiocephalic nerve was the only nerve to the extrinsic musculature that also formed a cutaneous nerve.

Long thoracic nerve. With invariant origin at C7 in the 20 *L. gymnocercus* plexuses dissected, the long thoracic nerve followed a horizontal path and stood out from the others in the thoracic portion of the serratus ventralis muscle, supplying it. This description of origin, route and innervation area is identical to that of the

domestic dog (Evans and De Lahunta, 2013) and *C. thous* (Souza Junior et al., 2014b). The origin of this nerve from C7 and C8 has been reported, among various species, in the domestic dog (Getty, 1986) and *A. australis* (Souza et al., 2010).

Pectoral nerves. The cranial pectoral nerves in *L. gymnocercus* had six different starting points, with predominance of C7 alone (40%). This result agrees with that reported by Getty (1986) and Evans and De Lahunta (2013) for dogs, in which this nerve is highly irregular with respect to branches and origin, but most often comes from C6, C7 and C8, alone or in combinations. This was also verified in 75% of the *L. gymnocercus* plexuses, while 25% had discrete contributions from T1. The cranial pectoral nerves supplied the superficial pectoral muscle, as also reported for the dog (Getty, 1986), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b).

The caudal pectoral nerves also presented different formation patterns, but the combination of C8 and T1 predominated (45% of the cases), as also described for *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). The T1 branch was present in 90% of the plexuses, confirming the more caudal origin in comparison with the cranial pectoral nerve. In studying six domestic dogs, Sharp et al. (1991) determined that C8 participated in the formation of all the caudal pectoral nerves, while T1 contributed in 66% and C7 in only 16%. The innervation distribution went to different areas of the deep pectoral muscle, as in dogs (Getty, 1986), *A. australis* (Souza et al., 2010), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b).

Some reports have described the origin of the pectoral nerves together, resulting in a larger number of roots in their formation. These studies reveal, for example, that the pectoral nerves come from C7 and C8 in domestic cats (Getty, 1986), C7, C8 and T1 in *A. microtis* (Pinheiro et al., 2013) and C6, C7, C8 and T1 in *A. australis* (Souza et al., 2010).

Thoracodorsal nerve. The thoracodorsal nerve came from the combination of C7 and C8 in 50% of the *L. gymnocercus* plexuses dissected, and also received a contribution from T1 in 45% of the cases. According to Evans and De Lahunta (2013), this nerve is formed by branch C8 with possible contributions from C7 and/or T1 in dogs, the same pattern observed in the pampas fox. In analyzing evoked potentials, Sharp et al. (1991) found that C7 and C8 were the most functional branches for this nerve in dogs. The thoracodorsal nerve has been reported to start from C6 alone in *A. australis* (Souza et al., 2010), C8 alone in *L. pardalis* (Chagas et al., 2014) and C8 and T1 together in *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). In the pampas fox, it was responsible exclusively for innervation of the latissimus dorsi muscle, as also the case for domestic dogs (Evans and De Lahunta, 2013), *A. australis* (Souza et al., 2010), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b).

Lateral thoracic nerve. The lateral thoracic nerve in *L. gymnocercus* started predominantly from C8

and T1 (45%), although other formations with discrete contributions from C7 also occurred in 35% of the cases. This formation between C8 and T1 has also been reported as most common in domestic dogs (Getty, 1986; Sharp et al., 1991; Evans and De Lahunta, 2013) and *C. thous* (Souza Junior et al., 2014b). Its innervation area included parts of the deep pectoral and cutaneous muscles of the trunk near the axillary regions, as also reported for the domestic dog (Evans and De Lahunta, 2013) and *C. thous* (Souza Junior et al., 2014b). In *A. australis* (Souza et al., 2010) it only innervates the cutaneous muscle of the trunk.

In conclusion, the brachial plexus of the pampas fox, *L. gymnocercus*, has identical origin and similar ramification to other carnivores species, especially domestic dogs (Allam et al., 1952), *A. microtis* (Pinheiro et al., 2013) and *C. thous* (Souza Junior et al., 2014b). Indeed, *L. gymnocercus*, *C. thous* and *A. microtis* inhabit the Neotropics and have the same number of chromosomes (74) (Pessutti et al., 2001). Therefore, it appears reasonable to assume that the similarities in the morphology of brachial plexus can reflect some phylogenetic proximity of these species. Studies of the plexuses of other wild canids may provide stronger evidence of that supposition.

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