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Vascularization of the lateral and medial antebrachial cutaneous nerves by cutaneous perforator arteries: An anatomical study

Vascularisation des nerfs cutanés latéral et médial de l'avant-bras par les artères perforantes cutanées : Étude anatomique

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Abstract

The forearm is an interesting donor site for non-vascularized nerve grafts, especially hand surgeons. Very few studies have described the use of the lateral and medial antebrachial cutaneous nerves (LABCN and MABCN, respectively) as vascularized nerve grafts (VNGs). The aim of this anatomical study was to analyze the characteristics and vascularization of these nerves to describe new potential donor sites for VNGs. Twelve forearms were dissected from fresh cadavers injected with red latex. The number of terminal branches, lengths, and proximal and distal diameters of both the LABCN and MABCN were studied. An anatomical description of the cutaneous perforator arteries from the radial and ulnar arteries that vascularized the nerve was also recorded: number of perforators, length, type of perforator (septo- or musculocutaneous), and location within the forearm (proximal, middle, and distal third). In over 80% of the specimens, the cutaneous perforator arteries from the radial and ulnar artery vascularized the LABCN and the MABCN, respectively. These arteries, found mostly in the proximal third of the forearm, had diameters >0.5 mm. Most of them came from the radial and ulnar arteries (for LABCN and MABCN vascularization, respectively). In over 75% of the specimens, the nutrient arteries of both nerves also vascularized the superficial veins and the skin. We found that these nerves are vascularized by perforators arteries, which also participate in vein and skin vascularization. Altogether, this anatomical study shows that reconstructive surgeons could use new VNGs based on the perforator artery of the forearm.

Résumé

L'avant-bras est un site donneur intéressant de greffe nerveuse non vascularisée. Très peu d'études se sont intéressées à l'utilisation des nerfs cutanés latéral et médial de l'avant-bras (NCLAB et NCMAB) comme potentielle greffe nerveuse vascularisée (GNV). L'objectif de cette étude anatomique était d'analyser les caractéristiques et la vascularisation de ces

nerfs afin de décrire de nouveaux sites de GNV. Douze avant-bras ont été disséqués à partir de cadavres fraîchement injectés de latex rouge. Le nombre de branches terminales, la longueur et les diamètres proximaux et distaux des NCLAB et NCMAB ont été étudiés. Les caractéristiques anatomiques des artères perforantes cutanées des artères radiale et ulnaire qui vascularisent ces nerfs sont également rapportées : nombre d'artère perforantes, longueur, type (septo- ou musculo-cutané) et localisation dans la région de l'avant-bras (tiers proximal, moyen et distal). Dans plus de 80 % des cas, les artères perforantes cutanées de l'artère radiale ou ulnaire participaient à la vascularisation des NCLAB et NCMAB respectivement. Ces artères, situées pour la plupart dans le tiers proximal de l'avant-bras, avaient un diamètre > 0,5 mm et provenaient des artères radiale (NCLAB) et ulnaire (NCMAB). Dans plus de 75 % des cas, ces artères vascularisaient également les veines superficielles et la peau. Nous avons observé que ces nerfs sensitifs superficiels de l'avant-bras étaient vascularisés par des artères perforantes cutanées. Ces artères participent également à la vascularisation des veines superficielles. Au total, cette étude anatomique indique que les chirurgiens reconstructeurs pourraient utiliser de nouveaux nerfs vascularisés basés sur les artères perforantes de l'avant-bras.

Keywords: Nerve vascularization; Vascularized nerve graft; Forearm cutaneous nerves; Lateral antebrachial cutaneous nerve; Medial antebrachial cutaneous nerve; Palmar digital nerve repair; Anatomical study; Perforator artery; Perforator flap

Mots-clés : Vascularisation nerveuse; Greffe nerveuse vascularisée; Nerfs cutanés de l'avant-bras; Nerf cutané latéral de l'avant-bras; Nerf cutané médial de l'avant-bras; Réparation des nerfs digitaux palmaires; Étude anatomique; Artère perforante; Lambeau perforant

1. Introduction

The forearm is an interesting donor site for nerve reconstruction, especially for hand surgeons. Non-vascularized superficial cutaneous nerve grafts are usually used as donor sites in the forearm. They can be easily raised into the subcutaneous tissue of the forearm with low donor site morbidity [1–5]. This makes them the ideal nerves for upper arm—especially digital nerve—reconstructions [3–6]. These nerves are usually used as non-vascularized nerves but can be used as vascularized nerve grafts (VNGs). For this, the exact anatomy of the vasculature supplying the superficial cutaneous nerves should be well known.

Few studies have focused on this vascular anatomy of the superficial cutaneous nerves of the body. Taylor et al. examined the source arterial supply of each peripheral nerve in the extremities and assessed the potential of each nerve's segment for VNGs [7,8]. Most of the studies assessed deep subfascial nerves (e.g.: median or sciatic nerves) and did not focus on superficial cutaneous nerves (e.g.: sural or saphenous nerves). In 1998, Nakajima et al. described the anatomy of the source artery for the superficial cutaneous nerves and veins in the extremities [9]. Similar to Taylor et al., Nakajima et al. found that arteries that vascularized cutaneous nerves of the upper and lower extremities were cutaneous perforator arteries [7,9]. Then, Masquelet et al. showed in an anatomical and clinical study of the leg that the vascularization of the superficial nerves (sural, saphenous, and superficial fibular nerves) comes from septocutaneous arteries arising from a deep source vessel [10]. In addition, these arteries gave off several cutaneous branches in the suprafascial course of the nerve. These results provided the basis for the design of skin flaps along neurovascular systems—the neuroskin flap [10]. Bertelli et al. studied the vascularization of the sensory nerves of the forearm in order to describe neurocutaneous axial island flaps to cover defects in the distal part of the forearm and the hand [11–13]. Vascularization of nerves of the upper and lower extremities came from cutaneous perforator arteries [9,14].

To the best of our knowledge, very few studies have described the use of the lateral and medial antebrachial cutaneous nerves (LABCN and MABCN, respectively) as VNGs

[15,16]. Like the superficial cutaneous nerve of the leg (e.g.: sural and saphenous nerves), we believe that these two forearm nerves (LABCN and MABCN) could be potential new donor sites for VNGs. In this anatomical study, we wanted to investigate the vascular anatomy of the LABCN and MABCN, describing the origin, localization, and anatomical characteristics of the forearm's perforator arteries and veins that vascularize these two nerves to discuss the possibility of using them as free VNGs.

2. Materials and methods

2.1. Preparation of specimens and dissections

In this cadaver study, we used 12 forearms from fresh cadavers (within 5 days of death). All dissections were performed after red latex was injected into the vascular network, as described by Peng et al. [17]. No funding was needed since our facility's anatomy laboratory provided the specimens and the other materials used in the study free of cost. The brachial arteries were injected with 60 cm^3 of a red-colored latex solution (Esprit Composite, Paris, France) at the middle third of the arm. Next, the arms were placed in a refrigerator at 4°C for 48 hours. Dissections were performed by the same surgeon using 3.5x magnification loupes and a Vernier caliper (0.05 mm precision) made by Wiha Tools ® (Schonach, Germany).

2.2. Anatomical description of the forearm cutaneous nerves (LABCN and MABCN)

An incision was made on the palmar side of the forearm, from the elbow to the wrist crease. The dissection started with skin removal and proceeded with the raising of the suprafascial layer and the identification of the superficial veins, nerves, and arterial perforators. LABCN and MABCN were dissected from where they pierced the deep fascia to become superficial to the wrist crease. The following characteristics were recorded for LABCN and MABCN: number of terminal branches, length of the fascial piercing point to the wrist crease, and the proximal diameters of the main branch (anterior division of both nerves).

2.3. Anatomical description of nerve vascularization

We dissected the cutaneous perforator arteries with a proximal diameter >0.5 mm (named "clinically significant" perforators) originating from the radial and ulnar arteries. The following characteristics were recorded for perforators with a diameter > 0.5 mm: number of perforators, length of the perforator artery from its source artery (radial or ulnar artery) to its entry into the subcutaneous adipose tissue, type of perforator (septo- or musculocutaneous), and location within the forearm (proximal, middle, and distal third).

We named the nerve nutrient arteries "nerve perforating arteries" or "nerve perforators" as an analogy to the cutaneous perforating arteries. All nerve perforators were dissected from the cutaneous nerves to their origins in the source arteries of the upper limb (radial, ulnar, anterior, and posterior interosseous arteries). We highlighted the perforators with diameters >0.5 mm. We recorded their types according to the classifications described by Taylor et al. and Nakajima et al. [9,18]. We measured the perforators' lengths and recorded the positions of their meeting points with the nerves along a proximal to distal axis between the elbow and wrist creases and divided them into proximal, middle, and distal thirds (Fig. 1). We also described the vascular intrinsic and extrinsic neurovascular systems of the nerves. The presence of neurocutaneous arteries or common vascularization with a vein was recorded.

2.4. Statistical analysis

The data are presented as mean ± standard deviation (SD) and were processed using Microsoft Excel 2008 (Microsoft Corp, Redmond, Washington).

3. Results

3.1. Lateral antebrachial cutaneous nerve (LABCN)

3.1.1. Anatomical characteristics

The LABCN is the terminal sensory branch of the musculocutaneous nerve. After supplying the coracobrachialis, biceps brachialis, and brachialis muscles, the musculocutaneous nerve

continues its course between the brachialis and biceps brachialis. It then goes under the lateral margin of the biceps tendon until it finally pierces the deep fascia to become a superficial and sensory nerve (innervating the lateral aspect of the anterior and posterior forearm).

First, we found that the LABCN divided into two or three terminal branches (2.17 ± 0.58 mm) along its course in the forearm (named anterior or posterior division). We found this division of the LABCN at the level where the nerve reached the cephalic vein: junction of the proximal and middle thirds of the forearm (Table 1). The anterior branch was constant and had a larger diameter. It joined the region at the elbow crease under the basilic and cephalic antebrachial veins. The anterior branch measured more than 1.5 mm in diameter (1.66 ± 0.55 mm) and had a mean length of 200 ± 20 mm. The posterior branch was present in 92% of the specimens. It was lateral to the cephalic vein and to the muscle belly of the brachioradialis. Its mean diameter was 1.2 ± 0.48 mm, and its mean length was 140 ± 35 mm. When a third branch was present (25% of the specimens), it was located posteriorly and progressed down the posterior border of the muscle bellies of the brachioradialis and extensor carpi radialis longus muscles (Tables 1 and 2).

3.1.2. LABCN nerve vascularization

The LABCN received several nutrient vessels. All of these were provided by radial artery perforators in every dissection. We found that all LABCNs had both intrinsic and extrinsic neurovascular systems spanning their entire length, including the anterior and posterior divisions. In total, several segmental vessels (perforator arteries) participated in LABCN vascularization. There were 7-8 segmental perforator arteries in the forearm (all cutaneous perforators).

Regarding the anterior branch of the LABCN (Fig. 2), we found 3.7 ± 1.1 perforator arteries with diameters greater than 0.5 mm: 52% were in the proximal third, 35% in the

middle third, and 13% in the distal third (Tables 2 and 3). They were mostly (85%) direct cutaneous perforators (septocutaneous perforators). Their mean length was 22.3 ± 8.59 mm (Tables 2 and 4). The posterior branch of the LABCN was vascularized by 1.80 ± 0.92 perforators larger than 0.5 mm in diameter originating from the radial artery (Fig. 3): 50% were in the proximal third, 39% in the middle third, and 11% in the distal third (Tables 2 and 3). They were equally direct (septocutaneous) or indirect (musculocutaneous) cutaneous perforators (52% and 48%, respectively). Their mean length was 14 ± 9.26 mm.

Interestingly, upon reaching the nerve, the arterial perforator divided into multiple branches. These branches coursed towards the division branches of the LABCN and formed the perineural anastomotic network. In each case, we found that these perforator arteries gave rise to the entire length of the intrinsic neurovascular system. Likewise, these branches also consistently gave rise to an extrinsic neurovascular nerve branch. According to Nakajima et al., the LABCN is a radiated type of nerve, which means it divides into several branches to create a fan shape. The LABCN has a Type 2 cutaneous nerve vascularization (extrinsic neurocutaneous vascular system present in one or two branches and not in the others) [9]. Using the Taylor and Ham classification [7], we found that the LABCN has Type C vascularization (source artery provides a segmental blood supply via a long artery coursing on the surface of the nerve). In each dissection, perforator arteries larger >0.5 mm were accompanied by perforator veins. Two venae comitantes were usually found at the origins of the main vessels.

In the proximal two-thirds of the forearm where the nerve penetrated the deep fascia and ran superficial to it, most of the perforator arteries vascularized the LABCN and originated from the radial artery (septocutaneous perforator artery in most cases). The distal segmental vascularization of the LABCN seemed to be more connected to the fascial vascular plexus.

188 *3.1.3. Neurocutaneous and venous branch from perforator arteries (Fig. 4 and Table 2)*

189 Nutrient arteries of the nerve (neurocutaneous branches) also vascularized the skin in
190 92% of the cases and the cephalic vein in 80% of the specimens. All perforator arteries
191 came from the radial artery (Table 2).
192
193 3.2. Medial antebrachial cutaneous nerve (MABCN)
194 *3.2.1. Anatomical characteristics*
195 The MABCN travels down the arm medial to the brachial artery, then pierces the deep fascia
196 with the basilic vein, approximately in the middle of the arm, to become subcutaneous, and
197 runs to the elbow and the forearm. The MABCN provides sensory innervation to the skin of
198 medial forearm (Fig. 5).

199 In all our dissected specimens, the MABCN bifurcated into anterior and posterior
200 branches, proximal to the medial epicondyle (Table 1). The anterior branch crossed the
201 elbow between the medial epicondyle and the biceps tendon, usually in front of the
202 antebrachial basilic vein. It then travelled superficially to the flexor carpi ulnaris (FCU)
203 muscle and ended around 100 mm from the wrist in every dissection. Its mean proximal
204 diameter (1.61 ± 0.29 mm) at the flexion crease of the elbow was similar to the LABCN's
205 diameter. Its length was 189 ± 47 mm. A posterior branch was found in 100% of the
206 specimens dissected. It was medial to the FCU muscle belly and medial to the antebrachial
207 basilic vein. It was smaller than the anterior branch, with a mean diameter of 1.52 ± 0.45 mm
208 and a mean length of 145 ± 38 mm (Table 1). There was a third branch in one specimen,
209 which progressed down the forearm and posterior to the FCU muscle (Tables 4 and 5).
210
211 *3.2.2. MABCN nerve vascularization*
212 The MABCN received several nutrient vessels, provided either by ulnar artery perforators in
213 90% of the specimens or by brachial artery perforators in 10% of the specimens. In 2

specimens (17%), vascularization of the posterior branch was provided by the anterior interosseous artery perforator. In the cubital fossa, the perforator arteries directly entered the intrinsic blood supply to all MABCNs and to the anterior and posterior divisions. In total, several segmental vessels entered the MABCN. Six to seven segmental perforator arteries vascularized the MABCN in the forearm; most of them were cutaneous perforator arteries.

Regarding the anterior branch of the MABCN, 2 or 3 perforators (mean of 2.42 ± 1.24) larger than 0.5 mm in diameter were mostly located in the proximal (55%) or the middle third (32%) of the forearm. These were either indirect (38%) or direct (62%) cutaneous perforators. The indirect muscular perforators were most frequently located in the proximal third and emerged from the FCU's muscle belly. The direct perforators were found most often in the middle and distal thirds of the forearm. The mean length of the perforators that vascularized the anterior branch of the MABCN was 21.6 ± 11.91 mm (Tables 4 and 5).

Regarding the posterior branch of the MABCN, there were 1 to 2 perforators (1.16 ± 1.29) larger than 0.5 mm in diameter located mostly in the middle third of the forearm (52%) or in the proximal and distal thirds (28% and 20%, respectively). The perforators were mostly (80%) indirect (musculocutaneous). The mean length of the perforators that vascularized the posterior branch of the MABCN was 14.9 ± 11.91 mm (Tables 4 and 5).

Interestingly, upon reaching the nerve, the arterial perforator divided into multiple branches. These branches coursed towards the division branches of the MABCN and formed the perineural anastomotic network. In each specimen, we found that these perforator arteries gave rise to the entire length of the intrinsic neurovascular system and to the extrinsic neurovascular nerve branches like the LABCN did. According to Nakajima et al., the MABCN is a radiated type of nerve, which means that it divides into several branches to create a fan shape. It also has a Type 2 cutaneous nerve vascularization where the extrinsic neurocutaneous vascular system was present in only one or two branches [9]. According to the Taylor and Ham classification [7], we found that the MABCN had Type C vascularization.

This pertains to the source artery providing a segmental blood supply to a long artery that courses on the surface of nerves.

In each dissected specimen, perforator arteries larger than 0.5 mm were accompanied by perforator veins. Two venae comitantes were usually found at the origins of the main vessels.

In the proximal two-thirds of the forearm where the nerve penetrated the deep fascia and ran superficial to it, most of the perforator arteries vascularized the MABCN and originated from the ulnar artery (in most cases: septocutaneous perforator artery for the anterior division and musculocutaneous perforator artery for the posterior division). The distal segmental vascularization of the MABCN seemed to be more connected to the fascial vascular plexus.

3.2.3. Neurocutaneous and venous branch from perforator arteries

Nutrient arteries of the nerve (neurocutaneous branches) also vascularized the skin in 88% of the specimens and the antebrachial basilic vein in 78% of the specimens. All perforator arteries came from the ulnar artery (Fig. 5, Table 4).

4. Discussion

The vascular blood supply of nerves has been well studied over the centuries [9,18–21]. In 1892, French surgeons Quénu and Lejars were the first to describe the anatomy of the blood supply to the peripheral nerves [22]. Later, breakthroughs in the understanding of peripheral nerve vascularization were credited to Sir Sydney Sunderland, who demonstrated the relationship between source arteries and peripheral nerve vascularization [23]. He stated that the vascularization of the nerve is done by an interconnected vascular network of intrinsic systems (i.e.: intrinsic vascular network) reinforced by segmental extrinsic vessels from source vessels (i.e.: external vascular network) [23]. Based on these anatomical

descriptions, the idea that VNGs could be raised including both segmental intrinsic and extrinsic vessels was introduced as a new field of research for nerve reconstruction surgeons [14,24,25]. Taylor and Ham introduced the notion of free VNGs in 1976 on the basis of cadaver and animal studies [7,25]. Then, in 1983, Lebreton et al. showed that the brachial part of the ulnar nerve can be used satisfactorily as a free microsurgical transfer or pedicled on the superior ulnar collateral artery in cases requiring transplantation of a large nerve trunk [20]. Currently, free VNGs have become increasingly popular since they are useful in bridging large nerve gaps if the recipient bed is heavily scarred [26]. Lastly, Bertelli et al. studied the vascularization of the sensory nerves of the forearm in order to describe neurocutaneous axial island flaps in the forearm to cover defects in the distal part of the forearm [11–13]. Based on cadaver and animal studies, they found that the vascularization of the cutaneous nerves is connected with the vascularization of the skin [11].

In this anatomical study, we found, like others, that the LABCN and MABCN exhibit the same vascularization with a mean of 8 cutaneous perforator arteries per nerve, all along the forearm (Fig. 6). The source arteries originated from the radial artery for the LABCN or from the ulnar artery for the MABCN. Most were found in the proximal third of the forearm, forming a proximal cluster of perforators. In this cluster, these perforator arteries had a diameter > 0.5 mm and a mean length of almost 30 mm (Fig. 6).

Regarding LABCN vascularization, we found in all dissected specimens that a cutaneous perforator artery—the proximal radial perforator artery (also called the inferior cubital artery perforator)—provides branches for nerve and skin vascularization. This artery, first described by Lamberty and Cormack, is a constant artery found in the proximal third of the anterior forearm, with a mean diameter of 1 mm and a mean length of almost 40 mm [27–29]. The origin of this artery is 35 ± 5 mm distal to the midpoint of the interepicondylar line on the anterior aspect of the forearm on the medial side of the brachioradialis muscle [27,29].

Regarding the MABCN, we also found a constant proximal ulnar artery perforator with a mean diameter of 1 mm and a mean length of 25 mm in all dissected specimens. This

proximal perforator artery was located at the junction between the proximal and middle thirds of the line linking the medial humeral epicondyle and the pisiform in all our specimens, as described by Wei et al. [30].

More specifically, we found that these perforator arteries gave rise to two types of arteries that vascularized these nerves, both of which were neurocutaneous arteries. The first type was the intrinsic neurocutaneous artery consisting of the arteries of the epineurium and their branches to the skin. The second was the extrinsic neurocutaneous artery supplied by the cutaneous perforator arteries and their branches to the skin, and the superficial veins. The extrinsic branch can also be called the extrinsic neurocutaneous or neurovenous branch because it gives rise to cutaneous and venous branches. Hence, these anastomotic plexuses vascularize the LABCN and MABCN (intrinsic and extrinsic network), the antebrachial cephalic vein, and the skin. These perforator arteries seem to be predominantly related anatomically with nerves and skin. They were only secondarily associated with the veins because vein perforators were very small (impossible to measure).

Taylor et al. and Nakajima et al. also demonstrated that two types of arteries (intrinsic and extrinsic arteries) vascularized the cutaneous nerves of the upper extremity [9,18]. In their cadaver study, Nakajima et al. carefully described all these arterial branches for the superficial nerves. They found that there were many variations in the branching forms of the cutaneous nerves. In their study, all the cutaneous nerves in the extremities had an intrinsic neurovascular system through their entire length, but did not always have the extrinsic neurocutaneous arteries [9]. They also found that there were three different types of cutaneous nerve vascularization, depending on the presence of the extrinsic neurocutaneous vascular system. In Type 1, the extrinsic neurocutaneous vascular system is present along the main nerve trunk over its entire length. In Type 2, the extrinsic neurocutaneous vascular system is present only in one or two branches. In Type 3, the nerves do not have any extrinsic neurocutaneous vascular systems [14,19]. Nakajima et al. classified the LABCN and MABCN as Type 3 nerves [14,19] since they found no extrinsic neurovascular branches in these nerves. The lack of extrinsic neurovascular system is

compensated by the accompanying artery of the cutaneous vein running with the nerve. This accompanying artery was common to the nerve and the vein [19]. In all our dissected specimens, we found this accompanying artery (Figs. 4, 6) in both the antebrachial cephalic and basilic veins. We described this artery as an extrinsic neurovascular artery. However, we agree with Nakajima et al. that this artery arose all along the forearm between both the superficial nerves and veins [9]. This means that their vascularity could be hard to dissociate. Consequently, if a potential VNG is raised, both superficial nerves and veins can be used. It is interesting to note that similar results have been published by Doi et al. and Bulla et al. who described the sural and saphenous nerve grafts as having common vascularization with the superficial veins [31,32].

Restoring the continuity to a damaged nerve with defect remains challenging for reconstructive surgeons [8]. In some instances, VNGs are mandatory, especially when large nerve gaps in a heavily scarred bed need to be reconstructed; however, the use of VNGs in clinical practice is still controversial [2,7,26,33,34]. There are a few donor VNGs found in the literature: the superficial branch of the radial nerve based on the radial artery, the ulnar nerve based on the superior ulnar collateral artery, the superficial fibular (peroneal) nerve based on the fibular artery, the saphenous nerve based on the saphenous artery, and the sural nerve based on the superficial sural artery [31,32,35–37]. Most of these VNG free flaps were based on large local arterial vessels or arterialized veins with their accompanying vasa nervorum. Very few studies have described the use of perforator arteries and veins as source vessels for VNGs.

In 1981, Comtet et al. described a new type of VNG: the medial brachial cutaneous nerve vascularized by an artery arising from the brachial artery [19]. Interestingly, Doi et al., in 1987, showed in an anatomical and clinical study that a small VNG—the vascularized sural nerve graft—was supplied by the cutaneous perforator of the fibular artery or the muscular perforating branch of the posterior tibial artery [31]. In addition, they showed that the vascularized sural nerve graft could be sectioned into as many as four segments while safely maintaining each segment's vascularity to increase the size of the VNG. A monitoring

skin paddle can be raised with the nerve graft because of the conjoint vascularization of the nerve and skin. Although this is an extremely attractive technique, it seems difficult to apply. Hayashida et al. also described the use of a vascularized sural nerve graft on a fibular artery perforator for immediate reconstruction of the inferior alveolar nerve defects. They reported a good clinical result [38]. Finally, Bulla et al. demonstrated that the saphenous nerve is vascularized by an interperforator anastomotic network from the posterior tibial artery network. There was a venous drainage system allowed by the venous perforator in the great saphenous vein (GSV). This perineural anastomotic network vascularized the saphenous nerve, the GSV, and the skin [31]. Taken together, these studies suggest the possibility of using superficial subcutaneous VNGs in the lower extremities.

To the best of our knowledge, very few VNG donor sites in the upper extremities have been described [39,40]. Thus, our study focused on forearm sensory cutaneous nerves (LABCN and MABCN). These nerves can be useful donor sites for the reconstruction of nerve defects of the hand, fingers, or upper limbs. If needed in the upper extremities, these VNGs can be helpful because they can be raised in the same surgical sites, for example, for digital neurovascular bundle injury reconstruction. In addition, it has been shown that these nerves are very secure donor nerves with good diameters compared to digital nerves, and they do not exhibit functional morbidity [3–6,41]. Finally, the resulting scar on the ventral side of the forearm is visible but inconspicuous and well protected by the natural positioning of the arm.

As we have discussed before, since most of the perforator arteries were found in the proximal third of the forearm, a midline incision of about 30 or 50 mm in the proximal third of the forearm could theoretically allow the surgeon to harvest a VNG of the LABCN or the MABCN. In our anatomical study, we found one perforator artery with these two venous comitante from the radial and ulnar arteries in each dissected specimen. After dissecting both the nerve and superficial vein, distal to proximal, the pedicle of the VNG could theoretically be found 35 mm distal to the elbow crease. In most of the cases, we found that the pedicle had a diameter >0.5 mm with a length of almost 30 mm. The nerve flap would

need to be harvested with the superficial veins to avoid iatrogenic trauma of the accompanying extrinsic artery. Whether the surgeon needs to harvest the antebrachial basilic or the cephalic vein to avoid an extrinsic artery lesion during dissection could not be determined in this study. Since we found that the perforator arteries that vascularized the LABCN and MABCN also vascularized the skin, the surgeon could design a composite flap with vascularized nerve and skin paddle based on the same pedicle (Fig. 7) [15].

Two major limitations of this study warrant mention. First, the number of dissections was limited. Second, all measurements were performed manually with a digital caliper. Possible measurement errors could not be avoided. Nevertheless, the consistent results in this small sample and the meticulous measurements taken by the same surgeon decreased the risk of false results. Further clinical studies are needed to analyze the *in vivo* feasibility of this VNG.

5. Conclusion

Altogether, this anatomical study shows that reconstructive surgeons can use potential VNGs based on the perforator artery of the forearm, as already described for the vascularized sural nerve graft. The next step would be clinical application of these VNGs in forearm nerve reconstructions.

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The authors declare they have no conflict of interest.

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510 **Figure legends**

511 Fig. 1. Proximal-to-distal axis passing through the midpoint of the distal palmar flexion
512 crease of the wrist and the midpoint of the elbow crease.

513 Fig. 2. Anterior branch of the lateral antebrachial cutaneous nerve and perforator arteries
514 from the radial artery. *White arrowheads*: radial artery; *arrows*: perforator arteries; *white*
515 *stars*: LAbN; *black arrowheads*: neuro-cutaneous or neuro-venous vascularization.

516 Fig. 3. Posterior branch of the lateral antebrachial cutaneous nerve and perforator arteries
517 from the radial artery. *White arrowheads*: radial artery; *arrows*: radial artery perforator; *white*
518 *stars*: LAbN; *black arrowheads*: neuro-cutaneous or neuro-venous vascularization.

519 Fig. 4. Forearm dissection showing the proximal perforator of the radial artery.
520 Consistent proximal perforator of the radial artery (*PRAP*) with the cutaneous or
521 neurocutaneous branch (*black stars*), arterial extrinsic neurovascular system in their entire
522 length (*white stars*) of the lateral antebrachial cutaneous nerve (LABCN). *RA*: radial artery;
523 *ABCV*: antebrachial cephalic vein, *LF*: lacertus fibrosus

524 Fig. 5. Anterior branch of the medial antebrachial cutaneous nerve and perforator arteries
525 originating from the ulnar artery. *White arrowheads and in red*: ulnar artery (*UA*); *arrows*:
526 ulnar artery perforator; *white stars and in yellow*: medial antebrachial cutaneous nerve
527 (MABCN); *black arrowheads*: neuro-cutaneous arterial branch.

Fig. 6. Distribution of perforator arteries > 0.5mm that vascularized the lateral and medial antebrachial cutaneous nerve. LABCN: lateral antebrachial cutaneous nerve; MABCN: medial antebrachial cutaneous nerve; *RA*: radial artery; *UA*: ulnar artery

Fig. 7. Design of composite flaps combining a sensory superficial nerve, a superficial vein and a skin paddle vascularized by a cutaneous perforator artery. *PAP*: Proximal artery perforator with the cutaneous branch and two commitment perforator veins; *N*: nerve; *CV*: cephalic vein

Table titles

Table 1. General characteristics of the lateral and medial antebrachial cutaneous nerves *: Proximal diameter when piercing the deep fascia in the elbow area; **: distal diameter of the main anterior branch of LABCN and MABCN; *SD*: standard deviation

Table 2. Characteristics of the lateral antebrachial cutaneous nerve's (LABCN) vascularization. *a*: anterior branch of the *LABCN*; *p*: posterior branch of the *LABCN*; *Vp*: common branch from the perforator artery for vascularization of superficial vein; *Cp*: common vascularization with the skin (neurocutaneous branch); *SD*: standard deviation

Table 3. Location and characteristics of perforator arteries with a diameter > 0.5 mm that vascularize the lateral antebrachial cutaneous nerve (LABCN). *a*: anterior branch of the LABCN; *p*: posterior branch of the LABCN; *SD*: standard deviation

Table 4. Characteristics of the medial antebrachial cutaneous nerve's (MABCN) vascularization. *a*: anterior branch of the MABCN; *p*: posterior branch of the MABCN; *Vp*: common branch from the perforator artery for vascularization of superficial vein; *Cp*: common vascularization with the skin (neurocutaneous branch); *SD*: standard deviation

Table 5. Location and characteristics of perforator arteries with a diameter > 0.5 mm that vascularize the medial antebrachial cutaneous nerve (MABCN). *a*: anterior branch of the MABCN; *p*: posterior branch of the MABCN; *SD*: standard deviation

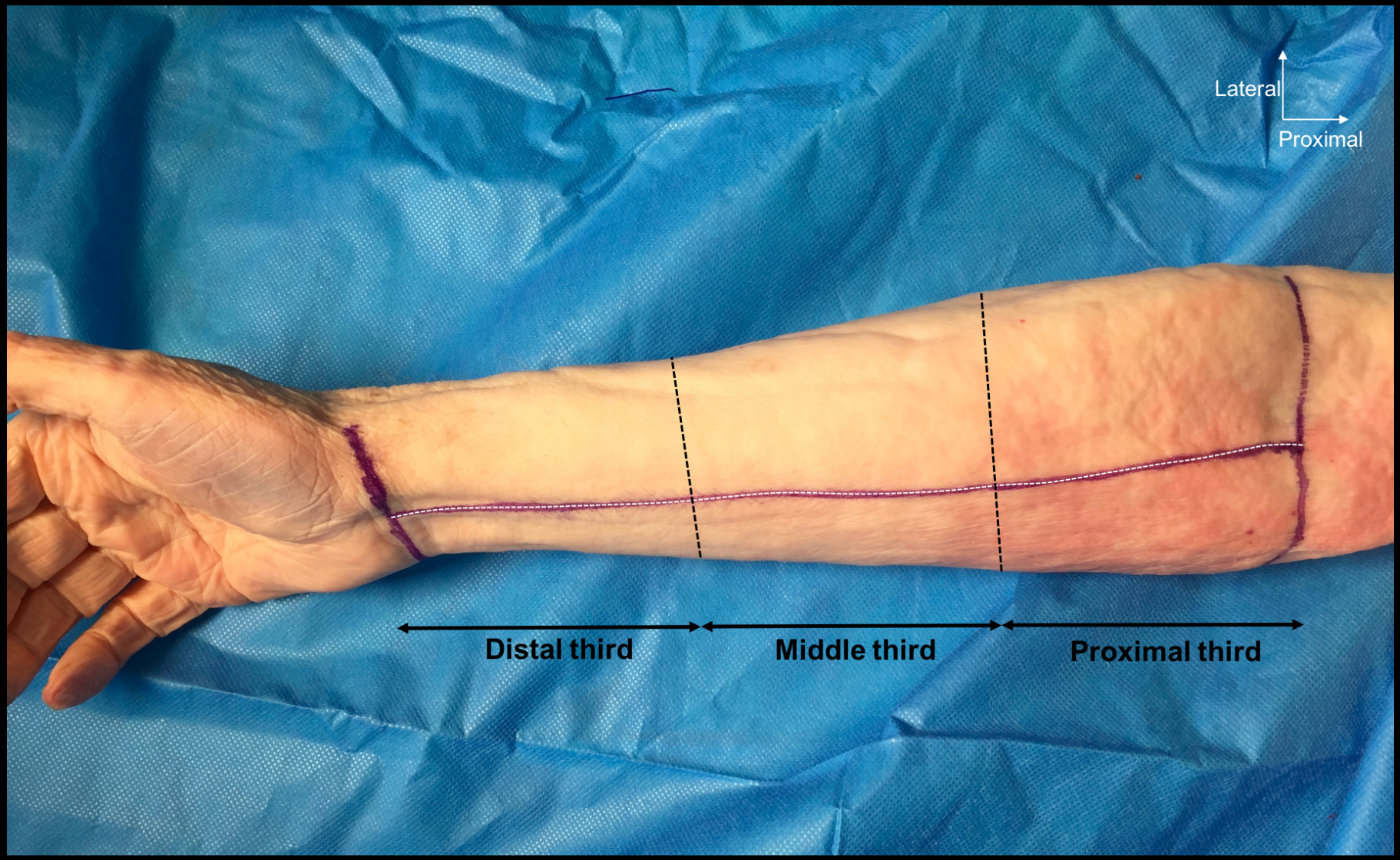

Lateral
Proximal
Distal third
Middle third
Proximal third

FIGURE 1

FIGURE 2

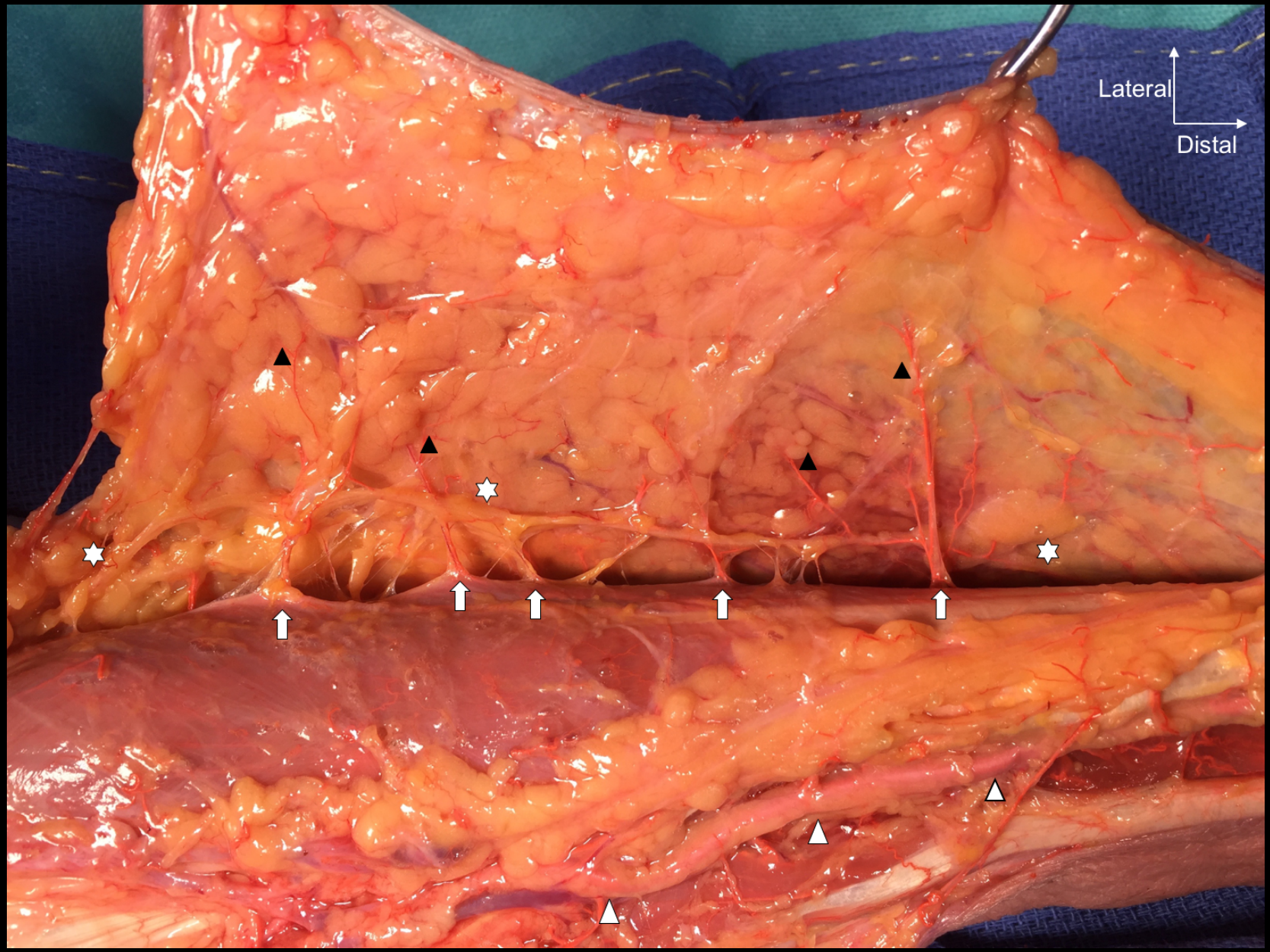
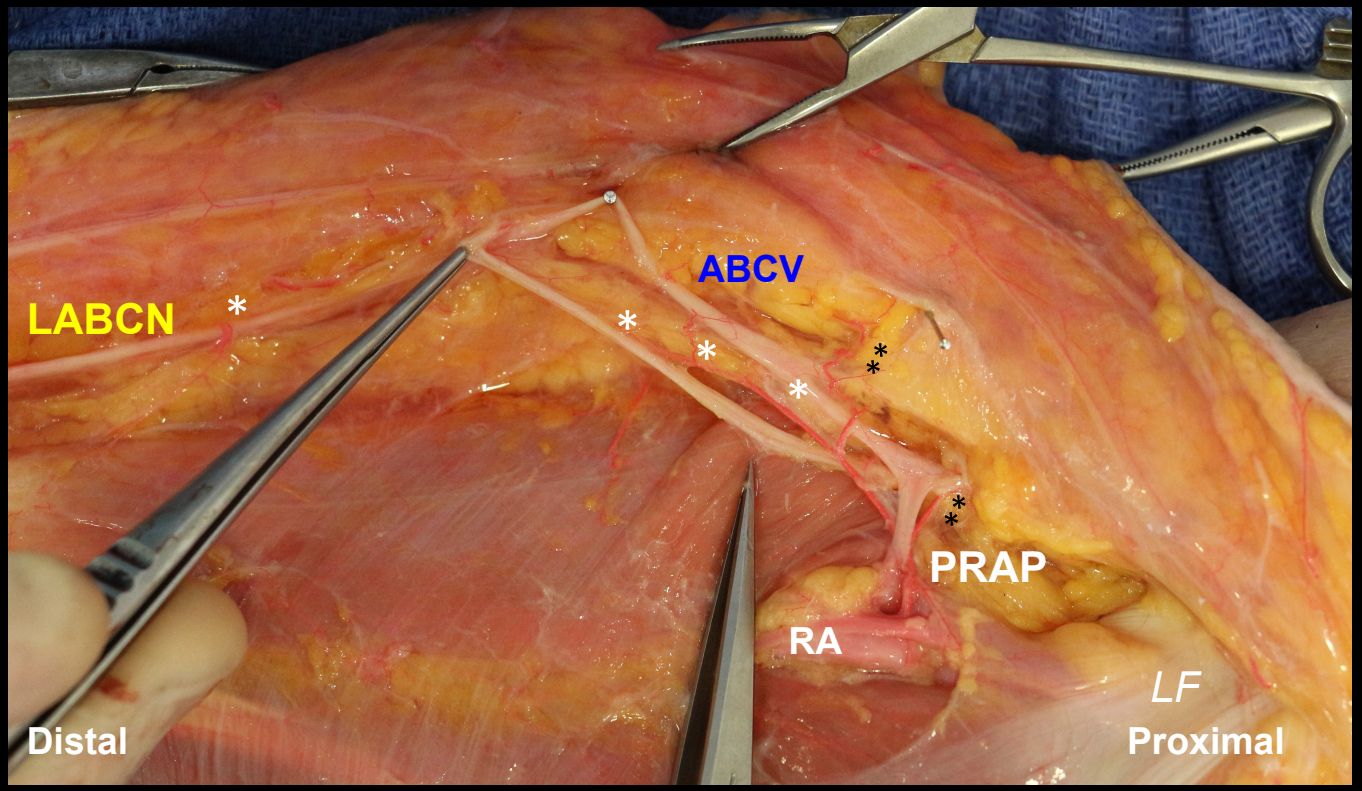


FIGURE 3


LABCN
ABCV
PRAP
RA
LF
Distal
Proximal

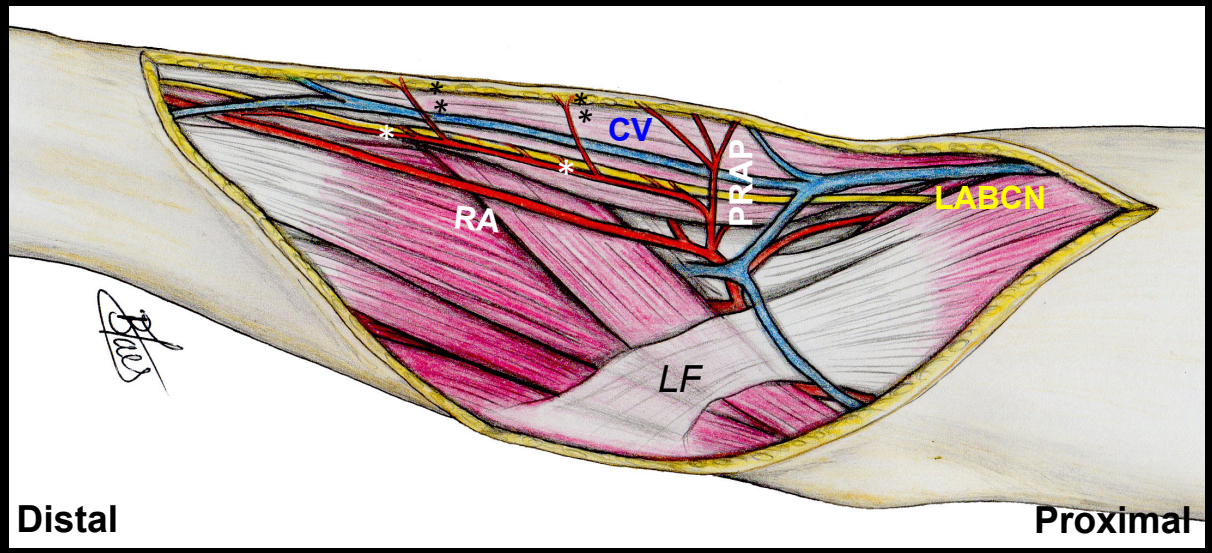

CV
PRAP
LABCN
RA
LF
Distal
Proximal

FIGURE 4

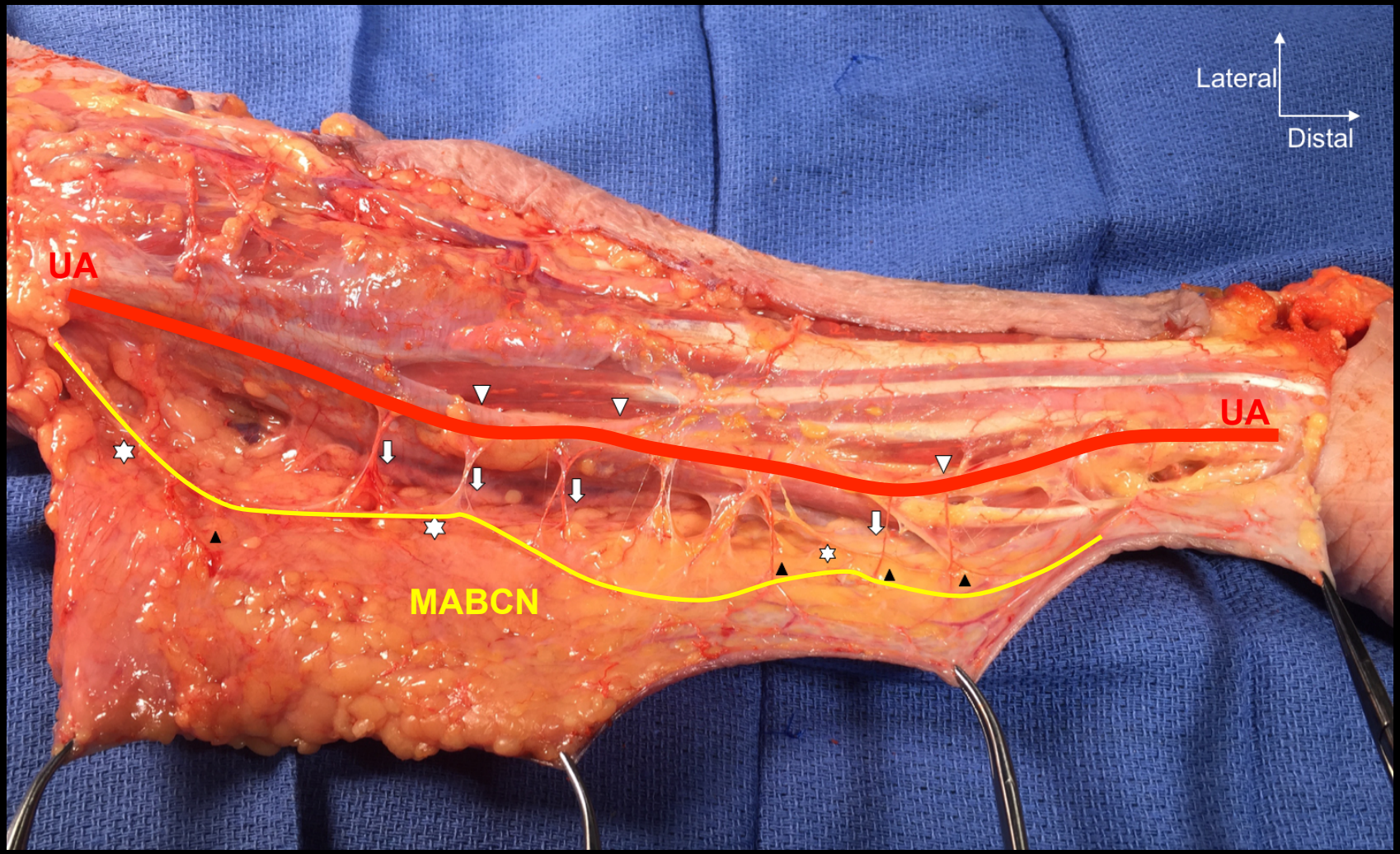
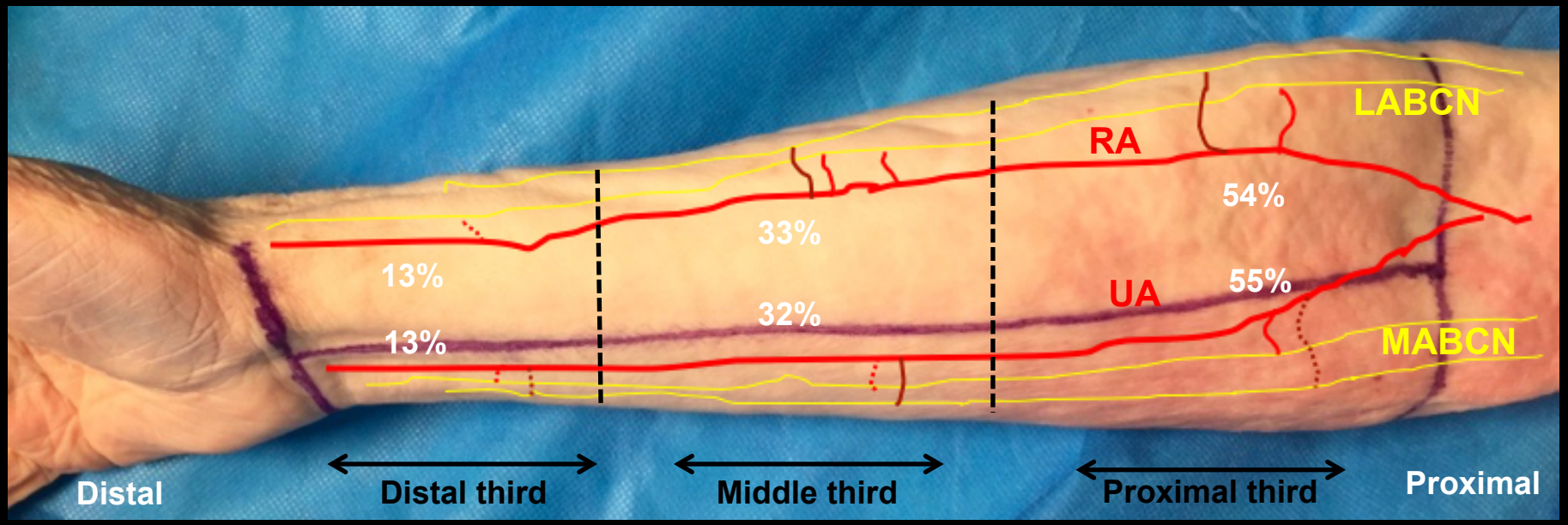


FIGURE 5



Direct perforator artery (septocutaneous)

Indirect perforator artery (musculocutaneous)

Superficial cutaneous nerve

FIGURE 6

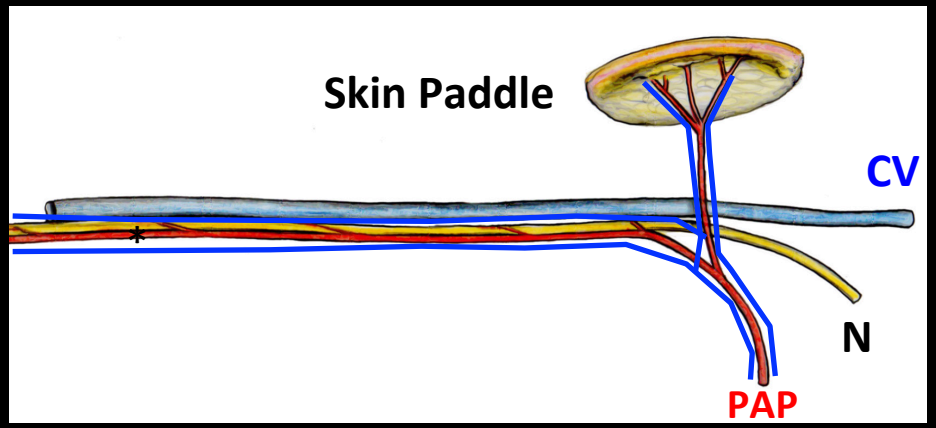


FIGURE 7

	lateral antebrachial cutaneous nerve (LABCN)			medial antebrachial cutaneous nerve (MABCN)		
Specimen	Number of terminal branches	Proximal nerve diameter (mm)*	Distal nerve diameter (mm)**	Number of terminal branches	Proximal nerve diameter (mm)*	Distal nerve diameter (mm)**
1	3	1.9	1.6	2	1.5	1.2
2	3	1.6	1.4	2	1.6	1.2
3	2	1.5	1.4	2	1.5	1.3
4	1	1.4	1.1	2	1.9	1.6
5	2	1.9	1.5	2	1.7	1.5
6	2	1.8	1.4	2	1.6	0.8
7	2	2.5	1.8	2	1.1	0.9
8	2	1.5	1.3	2	1.6	1.5
9	2	1.4	1.2	2	1.8	1.5
10	2	1.4	1.1	2	1.5	1.1
11	2	1.9	1.5	2	1.9	1.5
12	3	1.1	0.9	2	1.6	1.4
Mean	2.17	1.66	1.35	2	1.61	1.29
SD	0.58	0.37	0.25	-	0.29	0.27

Table 1. General characteristics of the lateral and medial antebrachial cutaneous nerves

*: Proximal diameter when piercing the deep fascia in the elbow area; **: distal diameter of the main anterior branch of LACN and MACN; *SD*: standard deviation

Specimen	Total number of radial perforator arteries vascularizing the LABCN branches		Total number of perforator arteries (> 0.5 mm) vascularizing the LABCN branches		Mean length of perforator artery (> 0.5 mm) vascularizing the LABCN branches (mm)		Presence of Vp (%)	Presence of Cp (%)
	aLABCN	pLABCN	aLABCN	pLABCN	aLABCN	pLABCN		
1	9	2	2	1	23	20	80	100
2	9	4	4	2	21	15	83	89
3	9	3	5	2	11	7	83	92
4	10	1	5	0	13	-	60	80
5	7	7	3	0	34	-	71	93
6	6	4	4	2	31	33	80	91
7	10	5	3	2	29	8	80	92
8	8	3	4	3	22	7	73	91
9	8	4	2	2	12	12	83	90
10	6	3	3	1	32	13	80	100
11	8	8	5	0	16	-	94	88
12	8	5	4	3	24	19	96	93
Mean	8.2	4.4	3.7	1.8	22.3	14	80	92
SD	1.4	1.8	1.1	0.9	8.1	8.6	9.6	5.2

Table 2. Characteristics of the lateral antebrachial cutaneous nerve's (LABCN) vascularization. *a*: anterior branch of the *LABCN*; *p*: posterior branch of the *LABCN*; *Vp*: common branch from the perforator artery for vascularization of superficial vein; *Cp*: common vascularization with the skin (neurocutaneous branch); *SD*: standard deviation

Specimen	Proximal third of the forearm				Middle third of the forearm				Distal third of the forearm				Number of musculo-cutaneous perforators				Number of septo-cutaneous perforators			
	aLABCN		pLABCN		aLABCN		pLABCN		aLABCN		pLABCN		aLABCN		pLABCN		aLABCN		pLABCN	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
1	1	50	1	100	1	50	0	-	0	-	0	-	2	22	1	50	7	78	1	50
2	1	25	0	-	1	25	0	-	2	50	2	100	2	22	1	25	7	78	3	75
3	1	20	1	50	1	20	1	50	3	60	0	-	1	11	1	33	8	89	2	63
5	3	100	0	-	0	-	0	-	0	-	0	-	2	28	2	29	5	78	5	71
6	2	50	0	-	2	50	2	100	0	-	0	-	1	16	1	33	4	84	3	84
7	2	67	2	1	1	33	0	-	0	-	0	-	3	30	2	33	7	70	3	70
8	4	100	2	67	0	33	1	33	0	-	0	-	3	37	1	33	5	63	2	64
9	2	100	0	-	0	-	2	100	0	-	0	-	0	0	2	50	8	100	2	50
10	1	50	1	100	1	50	0	-	0	-	0	-	1	16	2	67	5	84	2	33
11	2	40	0	-	3	60	0	-	0	-	0	-	2	25	3	37	6	75	5	63
12	3	75	1	33	1	25	2	67	0	-	0	-	1	12	2	40	7	88	3	60
Mean	2	52	1	50	1	35	0.89	39	0.58	13	0.22	11	1.83	15	1.44	48	3	85	1.11	52
SD	1.07	30	0.76	43	0.98	27	0.93	42	1.08	23	0.67	33	1.11	11	0.52	50	1.35	30	1.05	50

Table 3. Location and characteristics of perforator arteries with a diameter > 0.5 mm that vascularize the lateral antebrachial cutaneous nerve (LABCN). *aLABCN*: anterior branch of the LABCN; pLABCN: posterior branch of the LABCN; *SD*: standard deviation

Specimen	Total number of perforator arteries vascularizing the MABCN branches		Total number of perforator arteries (> 0.5 mm) vascularizing the MABCN branches		Mean length of perforator artery (> 0.5 mm) vascularizing the MABCN branches (mm)		Presence of Vp (%)	Presence of Cp (%)
	aMABCN	pMABCN	aMABCN	pMABCN	aMABCN	pMABCN		
1	7	7	4	4	18	16	87	100
2	3	3	0	0	-	-	75	75
3	8	4	2	1	16	10	75	93
4	5	3	2	0	33	-	66	83
5	5	5	3	2	25	20	63	91
6	14	4	2	2	29	27	79	95
7	7	2	1	0	17	-	80	90
8	7	3	2	2	8	4,5	90	72
9	5	2	3	0	26	-	83	83
10	5	4	2	0	27	-	67	83
11	9	4	4	3	15	12	78	93
12	6	3	4	0	23.5	-	60	86
Mean	6.75	3.67	2.42	1.16	21.59	14.91	78	88
SD	2.8	1.57	1.24	1.29	7.92	11.91	9.2	7.7

Table 4. Characteristics of the medial antebrachial cutaneous nerve's (MABCN) vascularization. *aMABCN*: anterior branch of the MABCN; *pMABCN*: posterior branch of the MABCN; *Vp*: common branch from the perforator artery for vascularization of superficial vein; *Cp*: common vascularization with the skin (neurocutaneous branch); *SD*: standard deviation

Specimen	Proximal third of the forearm				Middle third of the forearm				Distal third of the forearm				Number of musculo-cutaneous perforators				Number of septo-cutaneous perforators			
	aMABCN		pMABCN		aMABCN		pMABCN		aMABCN		pMABCN		aMABCN		pMABCN		aMABCN		pMABCN	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
1	1	25	1	25	1	25	1	25	2	50	2	50	4	57	4	57	3	43	3	43
2	-	-	-	-	-	-	-	-	-	-	-		1	33	0	0	2	77	0	0
3	1	50	-	-	1	50	1	100	-	-	-	-	3	38	1	25	4	62	3	75
4	2	100	-	-	-	-	-	-	-	-	-	-	2	40	0	0	3	60	0	0
5	2	67	-	-	1	33	2	100	-	-	-	-	2	40	2	40	3	60	3	60
6	1	50	1	50	-	-	1	50	1	50	-	-	4	28	2	50	10	72	2	50
7	1	100	-	-	-	-	-	-	-	-	-	-	4	57	1	50	3	43	1	50
8	-	-	-	-	1	50	1	50	1	50	1	50	3	43	1	33	4	57	2	67
9	1	33	-	-	2	67	-	-	-	-	-	-	1	20	0	0	4	80	0	0
10	1	50	-	-	1	50	-	-	-	-	-	-	2	40	0	0	3	60	0	0
11	3	75	2	67	1	25	1	33	-	-	-	-	2	22	1	25	7	78	3	75
12	2	50	-	-	2	50	-	-	-	-	-	-	2	33	0	0	4	67	0	0
Mean	1.36	55	0.8	28	0.91	32	1	52	0.36	13	0.6	20	1.27	38	2.2	80	1.36	62	0.2	20
SD	0.81	30	0.84	27	0.7	24	0	29	0.67	23	0.89	27	1.27	12.6	1.5	45	1.36	45	0.45	41

Table 5. Location and characteristics of perforator arteries with a diameter > 0.5 mm that vascularize the medial antebrachial cutaneous nerve (MABCN). *aMABCN*: anterior branch of the MABCN; *pMABCN*: posterior branch of the MABCN; *SD*: standard deviation