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Anatomical study of the medial calcaneal nerve using high-resolution ultrasound

Cecile Deniel¹ · Daphne Guenoun^{1,2} · Raphaël Guillin³ · Antoine Moraux⁴ · Pierre Champsaur^{1,2} · Thomas Le Corroller^{1,2}

Abstract

Objectives To determine whether high-resolution ultrasound (US) can identify the course and relations of the medial calcaneal nerve (MCN).

Methods This investigation was initially undertaken in eight cadaveric specimens and followed by a high-resolution US study in 20 healthy adult volunteers (40 nerves) by two musculoskeletal radiologists in consensus. The location and course of the MCN as well as its relationship to adjacent anatomical structures were evaluated.

Results The MCN was consistently identified by US along its entire course. The mean cross-sectional area of the nerve was 1 mm² (range 0.5–2). The level at which the MCN branched from the tibial nerve was variable, located a mean of 7 mm (range – 7–60) proximal to the tip of the medial malleolus. At the level of the medial retromalleolar fossa, the MCN was located inside the proximal tarsal tunnel a mean of 8 mm (range 0–16) posterior to the medial malleolus. More distally, the nerve was depicted in the subcutaneous tissue at the surface of the abductor hallucis fascia with a mean direct distance to the fascia of 1.5 mm (range 0.4–2.8).

Conclusions High-resolution US can identify the MCN at the level of the medial retromalleolar fossa, as well as more distally in the subcutaneous tissue at the surface of the abductor hallucis fascia. In the setting of heel pain, precise sonographic mapping of the MCN course may enable the radiologist to make diagnosis of nerve compression or neuroma, and perform selective US-guided treatments.

Clinical relevance statement In the setting of heel pain, sonography is an attractive tool for diagnosing compression neuropathy or neuroma of the medial calcaneal nerve, and enables the radiologist to perform selective image-guided treatments such as diagnostic blocks and injections.

Key Points

- *The MCN is a small cutaneous nerve which rises from the tibial nerve in the medial retromalleolar fossa to the medial side of the heel.*
- *The MCN can be depicted by high-resolution ultrasound along its entire course.*
- *In the setting of heel pain, precise sonographic mapping of the MCN course may enable the radiologist to make diagnosis of neuroma or nerve entrapment, and perform selective ultrasound-guided treatments such as steroid injection or tarsal tunnel release.*

Keywords Ultrasound · Cadaver · Adult · Heel · Neuroma

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Abbreviations

AH	Abductor hallucis
CSA	Cross-sectional area
ICN	Inferior calcaneal nerve
MCN	Medial calcaneal nerve
MR	Magnetic resonance
PTTS	Posterior tarsal tunnel syndrome
US	Ultrasound

Introduction

The medial calcaneal nerve (MCN) is a purely sensory branch of the tibial nerve that provides innervation to most of the heel pad and to the superficial tissues overlying the medial aspect of the calcaneus [1–3]. The MCN can present a variable origin [3–8]. Typically, it originates from the tibial nerve in the medial retromalleolar fossa just before its entry into the tarsal tunnel or within the proximal tarsal tunnel [3]. Sometimes, the MCN origin consists of two distinct trunks, with the proximal trunk branching from the tibial nerve as described above, and the distal trunk originating in the tarsal tunnel either from the tibial nerve bifurcation into the medial and lateral plantar nerves or from the lateral plantar nerve itself [3]. Then, in contrast, the MCN course and the distribution of its terminal branches appear to be quite constant [9]. The nerve is initially in a subfascial position deep to the fascia cruris and flexor retinaculum. Then, it pierces the flexor retinaculum and courses distally through subcutaneous tissues toward the medial aspect of the calcaneus. Finally, the MCN usually gives rise to two or three terminal branches destined for the medial and plantar aspects of the heel [3, 9].

Heel pain is a common presenting complaint in many clinical conditions, including plantar fasciitis, posterior tarsal tunnel syndrome (PTTS), Baxter's neuropathy, and stress fracture [10]. Entrapment, compression, or trauma specifically involving the MCN have been postulated as a potential cause of heel pain [11–16]. First, because of its initial course inside the proximal tarsal tunnel, the MCN may be involved in a compression syndrome in association with PTTS [2, 17]. Then, more distally, owing to its superficial course at the medial aspect of the calcaneus, the MCN may be subject to external compression and iatrogenic lesions [3, 9, 14]. Clinically, patients present with dysaesthesia, numbness, and neuropathic pain of the medial and plantar aspects of the heel.

The diagnostic evaluation of the peripheral nervous system classically involves a combination of patient history, physical examination, and electrodiagnostic studies [9]. Yet, because nerve conduction studies neither allow visualization of intrinsic abnormalities of peripheral nerves nor provide information about their relationship to adjacent anatomical structures, high-resolution ultrasound (US) has become an attractive complement for assessing the peripheral nervous system [18–20]. In the setting of a superficial neuropathy, US provides higher spatial resolution than magnetic resonance (MR) imaging and allows distinction between distal nerves and vessels making it the ideal imaging technique for the small cutaneous nerves of the extremities [21, 22]. Furthermore, US guidance has led to the development of a variety of peripheral nerve interventions such as diagnostic blocks, therapeutic injections, and even decompression “sonosurgery” techniques [23–26]. Yet, until now, compared with major nerves of the extremities, there has been a lack of detailed studies regarding the sonoanatomy of

the cutaneous nerves and their relevant entrapment syndromes [21, 22]. Because precise mapping of the MCN course may have significant clinical implications, such as diagnosing iatrogenic injuries or entrapment syndromes, guiding an elective neural injection, and avoiding injury to it during posterior tarsal tunnel release, the aim of our study was to determine whether US can identify this small cutaneous nerve and its relations to adjacent anatomical structures.

Materials and methods

Anatomical correlation

In accordance with the safety and ethics regulations of the institutions involved, this study was initially undertaken on eight formalin-embalmed cadaveric lower limbs amputated at the proximal leg level (three males and one female, mean age at death 86 years) to preliminarily assess the US depiction of the MCN and gain a better understanding of its anatomical course. None of the cadavers showed prior evidence of external foot injuries or surgical procedures on the ankle and foot region. The specimens were placed in lateral rotation and were examined using a commercially available US equipment (*Aplio i800*; Canon Medical Systems) with an 8–22 MHz hockey stick probe. A staff radiologist with 9 years of experience in musculoskeletal imaging and dissection and a fellow in musculoskeletal radiology performed each US examination and reached a consensus. Sonographic examinations were performed from the medial retromalleolar groove to the medial side of the calcaneus with the probe in short-axis slid along the nerve proximal-to-distal and distal-to-proximal. Identification of the fascicular echotexture was used to identify nerves on US [2, 12, 18, 22]. As previously reported, the visibility of the MCN was scored according to a four-level scale: 0—not visible; 1—identified with difficulty; 2—clearly identified without internal nerve structure visibility; and 3—clearly identified with internal nerve structure visibility [27]. The cross-sectional area (CSA) and thickness of the MCN were recorded on short-axis images. Because bony landmarks are generally more reliable for nerve detection than soft-tissue references, the craniocaudal distance between the MCN origin and the distal tip of the medial malleolus (D1) and the anteroposterior distance between the MCN origin and the posterior border of the medial malleolus (D2) were measured using US (Fig. 1). More distally, at the level of the calcaneus, the direct distance between the MCN and the fascia of the abductor hallucis (AH) muscle (D3) was also measured. Then, to validate the US data, China ink was injected under real-time US guidance in contact with the presumed MCN using a 22-gauge needle. Finally, a cadaver dissection was performed in six out of eight anatomic specimens. A skin and subcutaneous flap was reflected from the medial malleolus to the posterior aspect of the calcaneus.

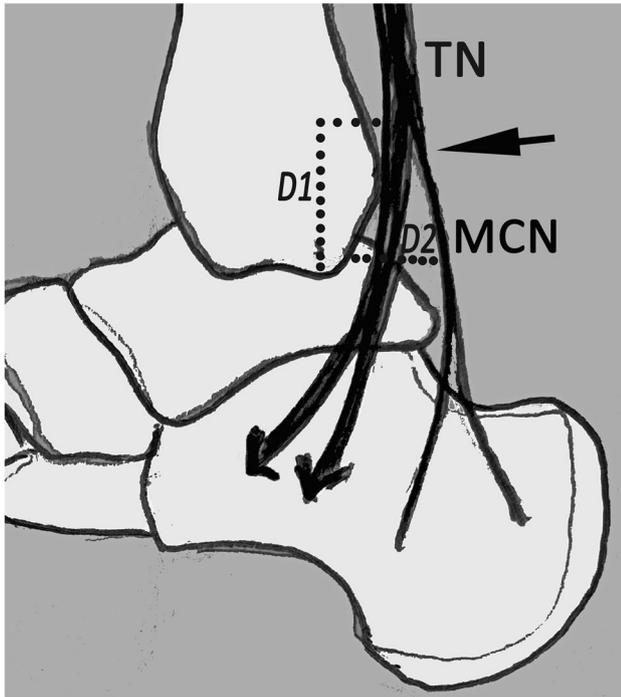


Fig. 1 Medial schematic anatomical view of a right foot illustrating the medial calcaneal nerve (MCN) originating from the tibial nerve (TN) in the medial retromalleolar fossa, and the craniocaudal distance between the MCN origin (arrow) and the distal tip of the medial malleolus (D1) as well as the anteroposterior distance between the MCN origin and the posterior border of the medial malleolus (D2). Distally, the TN bifurcates into the medial and lateral plantar nerves within the posterior tarsal tunnel whereas the MCN gives rise to two (or three) terminal branches in the subcutaneous tissues of the medial heel region

The tibial nerve, medial and lateral plantar nerves, and inferior calcaneal nerve (ICN) were identified in the tarsal tunnel (Fig. 2). The course of the MCN was specifically analyzed, and the three previously defined distances (D1, D2, D3) were measured again. The remaining two specimens were placed at -20°C for 48 h; and horizontal gross anatomical slices were obtained at the level of the tarsal tunnel to provide direct correlation with the exact same sonographic images (Fig. 3).

Ultrasound in vivo examination

After giving their informed consent, twenty healthy adult volunteers, ten males, and ten females (mean age 38 years, age range, 27–57 years) with a mean body mass index (BMI) of 23.5 (range 17.7–29.4) participated in this study. The volunteers presented no traumatic or surgical history, and no symptoms referable to the peripheral nervous system. A second team of two operators with differing expertise, an academic radiologist with 15 years of experience in musculoskeletal imaging, and a fellow in musculoskeletal radiology performed each US examination and again reached a consensus. Patients were examined in the supine position with lateral rotation of the foot using an *Aplio i800* (Canon Medical Systems) with an

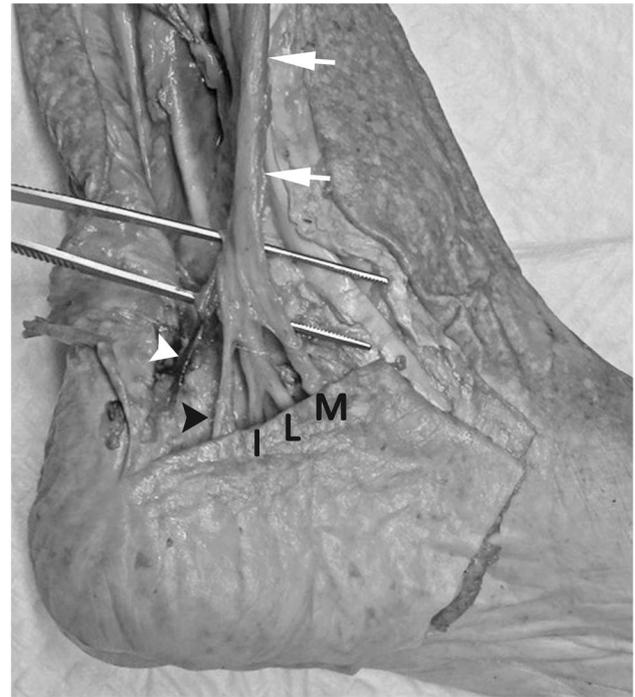


Fig. 2 Medial view of a dissected left foot showing the superior trunk of the MCN (white arrowhead) injected with China ink and the inferior trunk of the MCN (black arrowhead) that was not identified sonographically and therefore not injected with China ink. The TN (arrows) divides into the medial plantar nerve (M) and lateral plantar nerve (L) within the posterior tarsal tunnel. The inferior calcaneal nerve (I) originates from the lateral plantar nerve

8–22-MHz hockey stick probe. Initially, the probe was placed at the medial retromalleolar fossa in a transverse direction about six fingerbreadths proximal to the medial malleolus tip [28]. At this location, the probe was slid along proximal-to-distal until the MCN could be identified as a distinctive nerve that was separated from the tibial nerve. Probe compression and power Doppler were used in all examinations to differentiate the nerve from the adjacent vessels. The visibility, CSA, thickness, and course of the MCN as well as its relations to the surrounding structures were analyzed in real time while imaging. The previously defined distances between the nerve origin and respectively the distal tip of the medial malleolus (D1) and posterior border of the medial malleolus (D2), and, more distally, at the level of the calcaneus, between the nerve and the fascia of the AH muscle (D3) were recorded bilaterally. In case the MCN consisted of two distinct trunks, the proximal trunk only was considered when D1, D2, and D3 were recorded.

Results

The anatomical data obtained from the cadavers are shown in Table 1. In every cadaveric specimen, the axial US images identified a small hypoechoic ovoid structure along the

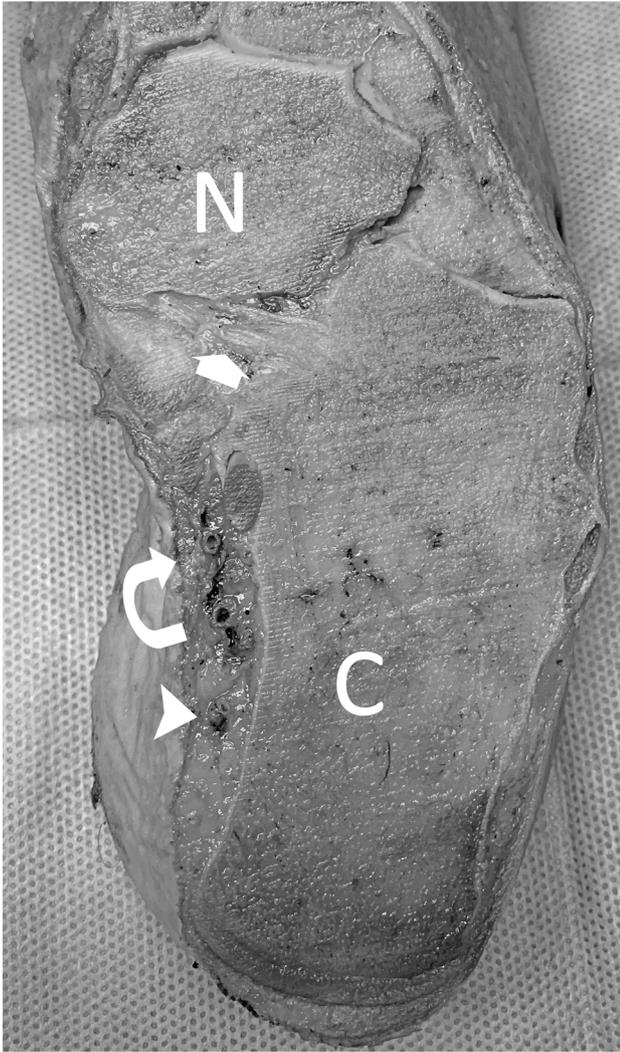


Fig. 3 Horizontal anatomical slice at the level of the spring ligament (thick arrow) that connects the calcaneus (C) with the navicular bone (N). The medial and lateral plantar vessels are accompanied by the medial and lateral plantar nerves (curved arrow) at the exit of the distal tarsal tunnel. Posteriorly, the MCN (arrowhead) appears injected with China ink and courses superficially at the medial aspect of the calcaneus

theoretical course of the MCN (Fig. 4). The China ink could be injected in the vicinity of the nerve under US guidance in every case at its point of branching from the tibial nerve in the medial retromalleolar fossa. The mean visibility score of the MCN was 2 (range 1–3). The mean CSA of the nerve was 1 mm² (range 0.7–2) and the mean nerve thickness was 0.7 mm (range 0.5–1.6). The MCN origin was located a mean of 15 mm (range 0–75) proximal to the medial malleolus tip (D1), and 10 mm (range 5–17) posterior to the medial malleolus (D2). More distally, the mean direct distance between the nerve and the AH fascia (D3) was 1.2 mm (range 0.2–2.3).

Subsequent cadaver dissection confirmed that the injected structure visualized on US did represent the MCN (Fig. 2).

Table 1 Anatomical results of eight cadaveric specimens

	US results (n=8)	Anatomical dissection (n=6)
Nerve visibility score (0–3)	2 (1–3)	N/A
Cross-sectional area (mm ²)	1 (0.7–2)	N/A
Nerve thickness (mm)	0.7 (0.5–1.6)	N/A
D1 MM tip (mm)	15 (0–75)	10 (0–27)
D2 MM posterior border (mm)	10 (5–17)	8 (3–15)
D3 abductor hallucis (mm)	1.2 (0.2–2.3)	1.5 (0.4–2.8)

Data shown include the medial calcaneal nerve (MCN) visibility score (0, not visible; 1, identified with difficulty; 2, clearly identified without internal nerve structure visibility; 3, clearly identified with internal nerve structure visibility); the MCN mean cross-sectional area and mean thickness; and the mean distances, respectively, D1 between the MCN branching point and the medial malleolus (MM) tip, D2 between the MCN branching point and the MM posterior border, and D3 between the MCN and the abductor hallucis fascia

The mean D1, D2, and D3 distances measured anatomically in six out of eight specimens were 10 mm, 8 mm, and 1.5 mm. In a single specimen, the MCN origin consisted of two separate trunks (1/8; 12.5%). Interestingly, in this specimen, the proximal MCN trunk only was correctly identified during the US examination, whereas the distal MCN trunk was initially misinterpreted as the ICN. Retrospective analysis of this case showed that the distal MCN trunk in fact branched distally from the lateral plantar nerve, and coursed backward to the heel with an overall direction from the depth to the surface.

The US data obtained in 20 volunteers (40 nerves) are presented in Table 2. The mean visibility score of the MCN was 2 (range 1–3), which indicates that the nerve was clearly identified without clear internal nerve structure visibility. The mean CSA of the nerve was 1 mm² and the mean nerve thickness was 0.6 mm. The MCN origin was located a mean of 7 mm (range –7–60) proximal to the medial malleolus tip (D1), and 8 mm (range 2–16) posterior to the medial malleolus (D2). More distally, the mean direct distance between the nerve and the AH fascia (D3) was 1.5 mm (range 0.4–2.8). The MCN could be identified along the majority of its course, from its point of branching from the tibial nerve in the medial retromalleolar groove to the medial side of the calcaneus (Fig. 5). The MCN origin consisted of two trunks in only 2 out of 40 cases (2/40; 5%), with the proximal trunk branching from the tibial nerve and the distal trunk originating from the lateral plantar nerve. In some individuals, interestingly, the nerve did present a slight enlargement at the point where it pierced the flexor retinaculum which may be an asymptomatic anatomical condition (Fig. 6). Expectedly, the terminal branches of the MCN that supply sensation to the superficial tissues overlying the inferior aspect of the calcaneus were difficult to assess sonographically, given

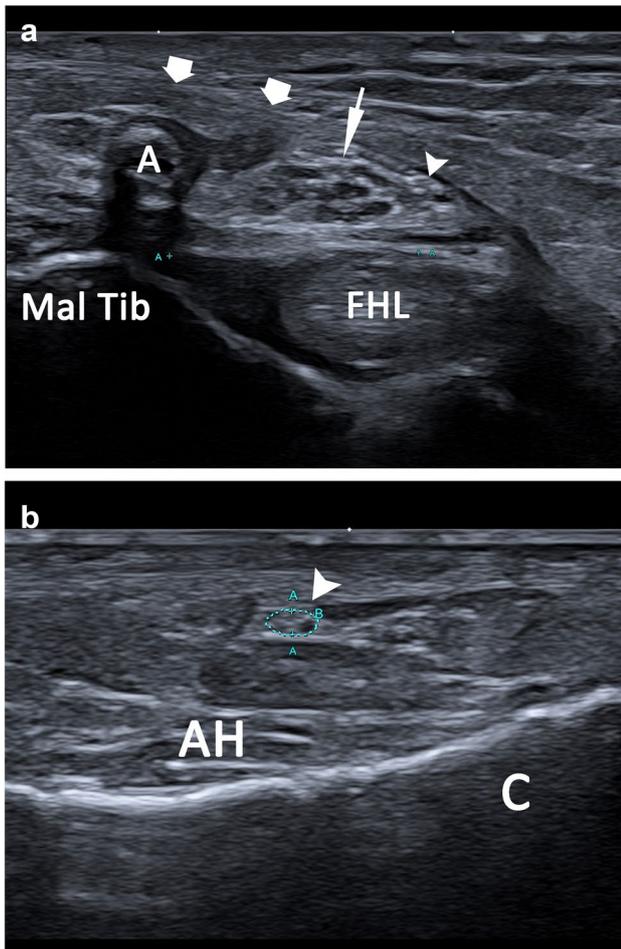


Fig. 4 **a** Horizontal sonographic image in a cadaver at the level of the retromalleolar fossa demonstrating the MCN (arrowhead) originating from the TN (arrow), and the anteroposterior distance (D2; calipers A) between the MCN origin and the posterior border of the medial malleolus (Mal Tib). The tibialis posterior artery (A) is heavily calcified. The flexor retinaculum is well demonstrated (thick arrows). **b** More distally in the same specimen, the MCN (arrowhead) is easily depicted in the subcutaneous tissue at the surface of the abductor hallucis (AH) muscle

their very small size and the adjacent hyperechoic subcutaneous fat. Overall, we observed that the nerve CSA, nerve thickness, and D2-D3 tended to be symmetric in the same individual, with D1 and the number of MCN trunks being the only variations sometimes noted from the right to left lower limb.

Discussion

The MCN is a small cutaneous nerve arising from the tibial nerve in the medial retromalleolar fossa that provides innervation to most of the heel pad [1–3]. Although the MCN origin may be variable with the existence of either one or

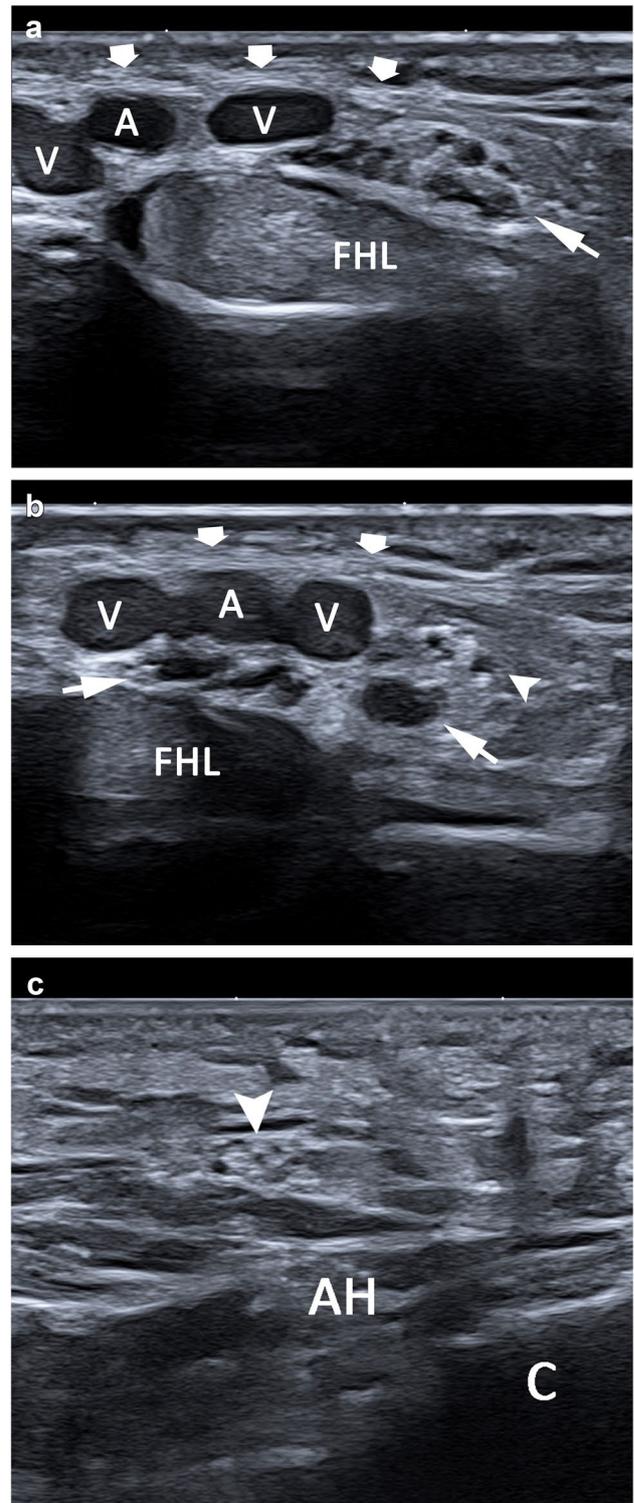
Table 2 Results for the 20 volunteers (40 nerves)

	US results
Mean age (year)	38 (27–57)
Mean BMI	23.5 (17.7–29.4)
Nerve visibility score (0–3)	2 (1–3)
Cross-sectional area (mm ²)	1 (0.7–2)
Nerve thickness (mm)	0.6 (0.5–0.8)
D1 MM tip (mm)	7 (–7–60)
D2 MM posterior border (mm)	8 (2–16)
D3 abductor hallucis (mm)	1.5 (0.4–2.8)

Data include demographics; the medial calcaneal nerve (MCN) visibility score (0, not visible; 1, identified with difficulty; 2, clearly identified without internal nerve structure visibility; 3, clearly identified with internal nerve structure visibility); the MCN cross-sectional area; and the mean distances, respectively, D1 between the MCN branching point and the medial malleolus (MM) tip, D2 between the MCN branching point and the MM posterior border, and D3 between the MCN and the abductor hallucis fascia

two main trunks that can branch from the tibial nerve or lateral plantar nerve proximal to or within the tarsal tunnel, its course and the distribution of its terminal branches appear in contrast to be quite constant [3, 9]. Initially, the nerve lies in a subfascial position deep to the fascia cruris and flexor retinaculum. Then, it pierces the flexor retinaculum and travels through the subcutaneous tissues toward the medial aspect of the calcaneus [3–8]. Owing to its initial course within the proximal tarsal tunnel, the MCN may be involved in the tarsal tunnel syndrome [12, 17]. Patients with PTTs present with paresthesia, hypoesthesia, or neuropathic pain affecting the heel or the sole of the foot. The precise location of symptoms may suggest which nerve branch is affected [17]. Pain in the heel suggests that the MCN or ICN are affected whereas pain in the medial or lateral borders of the foot indicates that respectively either the medial or lateral plantar nerve is affected [12, 17]. Altered biomechanics from pes planus with valgus hindfoot deformity, or any space-occupying lesion within this fibro-osseous tunnel such as accessory muscle, ganglion cyst, synovial process, or bony spur, can eventually cause symptoms [12, 17]. More distally, the MCN may also be subject to external compression and iatrogenic lesions along its superficial course at the medial aspect of the calcaneus [12–15]. The nerve is in particular susceptible to injury during calcaneal pin placement [12]. The diagnosis of MCN neuropathy usually requires confirmation using nerve conduction studies, especially when conservative treatment is unsuccessful [9]. On the other hand, high-resolution US is now considered the ideal imaging modality for assessing the cutaneous nerves of the extremities [18–22, 29]. The evaluation of these small nerves of caliber < 2 mm requires high-end equipment and higher frequency probes [18]. As these nerves can be too small for a reliable CSA measurement, the

Fig. 5 **a** Horizontal sonographic image in an asymptomatic volunteer at the level of the retromalleolar fossa demonstrating the TN (arrow) within the proximal posterior tarsal tunnel, as well as the tibialis posterior artery (A) and veins (V) deep to the flexor retinaculum (thick arrows). The flexor hallucis longus (FHL) tendon is located deep to the TN and is helpful to follow the TN and more distally the medial plantar nerve within the posterior tarsal tunnel. **b** Slightly more distally in the same individual, the MCN (arrowhead) is demonstrated deep to the flexor retinaculum (thick arrows) whereas the TN is already divided into the medial plantar nerve (anterior/left arrow) and lateral plantar nerve (posterior/right arrow). **c** At the level of the calcaneus (C), the MCN (arrowhead) is easily identified in the subcutaneous tissue at the surface of the abductor hallucis (AH) muscle



diagnosis may sometimes rely exclusively on pattern recognition [18]. Because precise mapping of the MCN course in the medial ankle area may have significant clinical implications, the aim of the present study was to determine whether US can identify the nerve and its relations with adjacent anatomical structures.

Our results show that, despite its relative thinness, the MCN could be identified sonographically along the majority of its course, from its point of branching from the tibial nerve in the medial retromalleolar groove to the medial side of calcaneus. The preferred technique for examination was dynamic, commonly referred to as the “elevator technique,” with the probe in short-axis slid along the nerve proximal-to-distal and distal-to-proximal [18]. This scanning technique provided a detailed morphologic study of the nerve and perineural structures. Compared with MR, a major advantage of US was its ability to distinguish the MCN from vessels using probe compression and power Doppler imaging. The point of optimal visibility of the MCN was just before the entry of the tibial nerve into the tarsal tunnel. More distally, the MCN could also be identified in the subcutaneous tissues as it lay at the surface of the AH fascia. In some individuals, the nerve presented a slight enlargement at the point where it pierced the flexor retinaculum which may be an asymptomatic anatomical condition. Distally, the MCN terminal branches that supply sensation to the medial and plantar aspects of the heel were more difficult to assess given their very small size. Because bony landmarks are helpful in reliably identifying anatomical structures with US, we evaluated both in cadavers and in asymptomatic individuals the distances between the MCN origin and the medial malleolus distal tip and posterior border respectively. In addition, because the MCN was particularly well-identified more distally as it lay at the surface of the AH muscle, the direct distance between the nerve and the AH fascia was also recorded. In the part of our work performed on cadavers, these three distances measured by US were similar to those measured anatomically. Then, in healthy volunteers, these same three distances measured by US fell within the range demonstrated anatomically. Besides, our study confirmed that the MCN can present a variable origin. Previous anatomical studies reflect the wide variation in the

proximal course of the MCN with the existence of either one or two main trunks that branch from the tibial nerve or lateral plantar nerve proximal to or within the posterior tarsal tunnel [3–8]. In our work, in one out of 8 cadaver specimens and in two out of 40 healthy ankles, the MCN origin did consist of two trunks, with a proximal trunk branching from the tibial

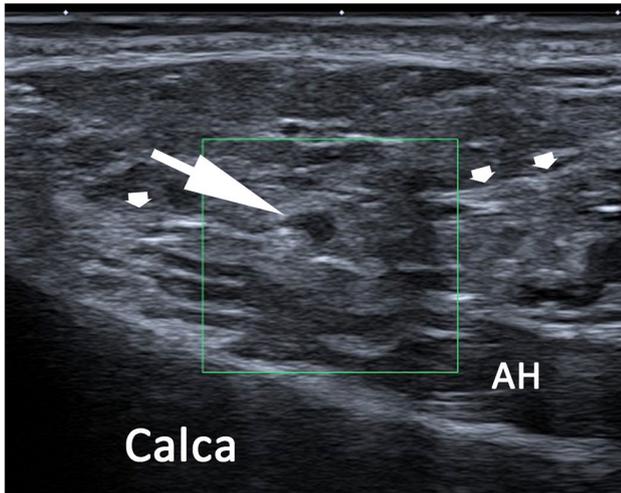


Fig. 6 Horizontal sonographic image obtained in another volunteer at the level of the calcaneus (C) and abductor hallucis (AH) showing a slight enlargement of the MCN (arrow) at the point where it pierces the flexor retinaculum (thick arrows) which may be an asymptomatic anatomical condition. Power Doppler was used to allow distinction with a vessel and demonstrates the absence of any internal flow

nerve as described above, and the distal trunk originating in the tarsal tunnel either from the tibial nerve bifurcation into the medial and lateral plantar nerves or from the lateral plantar nerve itself. In these cases, in contrast with the ICN that travels downward, forward, and laterally with a course passing the upper edge of the AH muscle and the medial edge of the quadratus plantae muscle, the distal MCN trunk presented an overall direction from the depth to the surface toward the heel. Despite variability of the MCN origin, the course and the terminal portion of the nerve were very consistent in all cadaver specimens and asymptomatic individuals evaluated in our study. Finally, our data suggest that the MCN may not only be subject to compression neuropathy at the level of the proximal tarsal tunnel, but also be at risk when performing a surgical approach to the medial aspect of the calcaneus.

We acknowledge some limitations of this study. First, we evaluated only eight cadaveric lower limbs, which is a relatively small number for an anatomical study. Second, we did not analyze the intra- and inter-observer variation in the US study of the MCN. In our work, the preliminary assessment of the MCN undertaken in cadavers as well as the US examinations in healthy volunteers were instead performed in consensus by two separate teams comprised of one fellow and one experienced staff radiologist. Third, we acknowledge that in the *in vivo* evaluation portion of the study the percentage of anatomic variation of the MCN origin was smaller (2/40; 5%) than in previous anatomical studies that report between 11 and 29% of multiple MCN trunks [3–8]. This plausible underestimation of the variation of the MCN origin may be related to a “satisfaction of

search bias” with sonographic identification of the MCN proximal trunk only [30]. Finally, the results obtained in our volunteer population might have been influenced by a “healthy” BMI facilitating the US depiction of the nerve. It is important to note that, in patients with a higher BMI, the course of the MCN may be more difficult to assess with US, given the small size of the nerve. However, pathological conditions of peripheral nerves usually result in an increased nerve caliber [18].

Because the anatomy of the MCN is known to vary between individuals, US mapping of this nerve may have useful clinical implications [31]. First, in the setting of PTTS, especially when conservative treatment is unsuccessful, sonography may become an attractive tool for diagnosing compression neuropathy of the tibial nerve and/or of its branches [17]. Second, because injury to the MCN has been reported after surgery, later resulting in neuralgia and sensory loss in its innervation area, US could help in the differential diagnosis of postoperative heel pain [12]. Then, US guidance can lead to the development of a variety of peripheral nerve interventions including the ability to perform selective treatments such as MCN diagnostic blocks and injections, or even US-guided posterior tarsal tunnel release [23–26]. In conclusion, our study has demonstrated that, in healthy individuals, high-resolution US can identify the MCN at the level of the medial retromalleolar fossa, as well as more distally in the subcutaneous tissue at the surface of the abductor hallucis fascia. The potential diagnostic and therapeutic applications of this technique now need to be evaluated by further clinical studies.

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Declarations

Guarantor The scientific guarantor of this publication is Pr Thomas Le Corroller.

Conflict of interest The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was obtained from all subjects (volunteers) in this study.

Ethical approval Institutional Review Board approval was not required because the study only involved anatomical specimens and volunteers who were recruited from the Department of Radiology.

Methodology

- prospective
- experimental
- performed at one institution

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