

MRI Study on Tibial Nerve of the Ankle Canal and Its Branches: A method of multiplanar reconstruction with 3D-FIESTA-C sequences

Yan Zhang

Feicheng Hospital of traditional Chinese Medicine of Shandong Province <https://orcid.org/0000-0002-7315-1446>

Xucheng He

Third Medical Center of Chinese PLA General Hospital

Juan Li

Third Medical Center of Chinese PLA General Hospital

Ju Ye

Third Medical Center of Chinese PLA General Hospital

Wenjuan Han

Third Medical Center of Chinese PLA General Hospital

Shanshan Zhou

Third Medical Center of Chinese PLA General Hospital

Jianzhong Zhu

The Second Affiliated Hospital of Shandong First Medical University

Guisheng Wang

Third Medical Center of Chinese PLA General Hospital

xiaoxia chen (✉ jingnhn828@163.com)

<https://orcid.org/0000-0002-2421-747X>

Research article

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Abstract

Background

The display of tibial nerve and its branches in the ankle canal is helpful for the diagnosis of local lesions and compression, and also for clinical observation and surgical planning. The aim of this study was to investigate the feasibility of three-dimensional dual-excitation balanced steady-state free precession sequence (3D-FIESTA-C) multiplanar reconstruction (MPR) display of tibial nerve and its branches of the ankle canal.

Methods

The subjects were 20 healthy volunteers (40 ankles), aged 22–50, with no history of ankle joint disease. 3D-FIESTA-C sequence was used in the 3.0T magnetic resonance equipment for imaging. During the scanning, each foot was at a 90-degree angle to the tibia. The tibial nerve of the ankle canal and its branches were displayed and measured at the same level through multiplanar reconstruction.

Results

Most of the tibial nerve bifurcation points were located in the ankle canal (57.5%), few (42.5%) were located at the proximal end of the ankle canal, and none was found away from the distal end. The bifurcation between the medial plantar nerve and the lateral plantar nerve is on the line between the tip of the medial malleolus and the calcaneus, and its angle is between 6° and 35° . The average cross-sectional diameter of the medial plantar nerve is about mm, and the lateral plantar nerve about mm. In MPR images, the display rates of both the medial calcaneal nerve and the subcalcaneal nerve were 100%, and the starting point of the subcalcaneal nerve was always at the distal end of the starting point of the medial calcaneal nerve. In 55% of cases, there were more than 2 medial calcaneal nerve innervations.

Conclusion

The 3D-FIESTA-C MPR can display the morphological features and positions of tibial nerve and its branches and the bifurcation point's projection position on the body surface can be marked. This method not only benefited the imaging diagnosis of tibial nerve and branch-related lesions of the ankle canal, but also provided a good imaging basis to plan the clinical operation of the ankle canal and avoid surgical injury.

Background

The malleolus canal is a fibrous bony channel behind the medial malleolus, with the anterior wall being the distal tibia, the posterior wall being the posterior talus and calcaneus, and the flexor support band

covering the surface. The anatomy of the tibial nerve and its major branches is largely determined by its position in the ankle canal [1]. The special anatomical structure and soft tissue space of the ankle canal makes the ankle canal syndrome the most common disease symptom in this area, and its occurrence is often closely related to the nerve compression [2, 3]. This not only leads to tibial nerve dysfunction and plantar pain, but also mainly causes heel pain and even abductor atrophy of the little toe [4]. It is noteworthy that this body part is used as a pathway in minimally invasive and surgical operations [5], ankle canal decompression, ankle canal incisions, and external nail fixation of fractures are likely to cause iatrogenic nerve injury [6–8]. At present, through the anatomic study of the tibial nerve and its branches at the ankle canal, the location and course of the nerve are determined, and the origin and quantity of the medial calcaneus nerve and the inferior calcaneus nerve at the ankle canal are classified [9–11], which provides a great help for the understanding of the nerve in the ankle canal. Using ultrasound to display the nerves in this area, and the injection of infracalcaneus nerve under the guidance of ultrasound can improve the injection accuracy [12, 13], but ultrasound can not display the whole shape of the nerves in a stereoscopic and intuitive way, and largely depends on the technology and experience of the operator. Some studies to initially discuss the display and diagnostic value of the ankle canal tibial nerve and branch through MR [14, 15]. Because of the 2D sequence and routine transverse, coronal and sagittal scanning, it is difficult to show and trace the tibial nerve and its branches in a large range on the same plane, and it is difficult to show the small branches clearly, and no more comprehensive study on the morphological types of medial calcaneus nerve and inferior calcaneus nerve. This study applied three dimensional double excitation balanced steady-state free precession sequence (3D-FIESTA-C) multiplanar reconstruction method, to show direction, position and branches of the nerve on the vertical axis direction according to the neural anatomy, and describe the origin of the different branches and position change. This benefited the MR diagnosis of peripheral neuropathy of the ankle tube, and also directly guided the clinical observation and surgical planning in image anatomy. The position of the nerve was successfully projected in the body surface through certain measurement method, which is necessary to ensure the safety of the operation around the ankle canal.

Methods

In our study, we used 40 ankle MRI images from 20 volunteers with an average age of 33.8 years (range from 22 to 50 years) who agreed to participate in the study and completed an informed consent. They had no history of ankle disease and no pain.

MR scan parameter

The special coil for the ankle joint was adopted, and the patient was supine, with the toe pointing vertically up and the foot at a 90-degree angle to the tibia. The patients' ankle was placed into the coil horizontally and fixed. See Table 1 for specific scanning parameters of the 3D-FIESTA-C sequence.

Table 1
The acquired parameters of The 3D-FIESTA-C
sequence

Acquired the Parameters	The Value
Scan Plane	Oblique(3d)
Slice Thickness	1.0
The TR	6.4
TE	3.0
Slabs	1
The Flip Angle	60
Frequency	288
Phase	288
NEX	2.00
Bandwidth	62.50
Matrix size	512 × 512
The SAR	3.0
The Time of acquisition	6 min 40 s - 7 min 28 s

Image reconstruction method

The collected images were loaded into the post-processing workstation and the MPR mode was launched. The specific reconstruction method is as follows: 1. Find the tibial nerve on the cross-sectional images, and set it as the center of rotation, and through MPR constantly and slightly rotate, making tibial display length increase to show the bifurcation between the medial plantar nerve and the lateral plantar nerve in Fig. 1A. Then put the center of rotation to the bifurcation point, show tibial nerve the medial plantar nerve and the lateral plantar nerve in the same plane through appropriate small rotation. Appropriately adjust wide window to improve the resolution and contrast of nerve; and measure the angle between the medial plantar nerve and the lateral plantar nerve in Fig. 1B. 2. Reconstruct the largest image through the medial plantar nerve and lateral plantar nerve, shown in Fig. 2. 3. Take the tibial nerve, the lateral plantar nerve and the longitudinal axis` of the medial plantar nerve as the rotation axis, rotate to see if there are any other branches. If there are branches, place the center of rotation on the bifurcation and display the branches at the maximum level as shown in Fig. 3A and 4B. Further segmental reconstruction was carried out to the nerve terminal to determine its dominant region and name. Meanwhile, the accuracy of the reconstructed image of the nerve should be checked against the cross-sectional image as shown in Fig. 3C and 3D. 4. Set two reference lines on the sagittal plane image: the projection of the horizontal line of the medial malleolus on this plane (Line1) and the projection of the

medial malleolus and calcaneus nodules on this plane (Line2). Determine the relationship between the bifurcation points and Line1 and Line2 on the sagittal plane images of the bifurcation points of the inner and outer plantar nerves. Measure the distance between the bifurcation point and the projection point of the medial ankle tip on the plane and the included Angle between the bifurcation point and the projection point of the medial ankle tip and Line1 in Fig. 4. For the convenience of marking, the angle of the bifurcation point above the horizontal line is positive, and the angle below the horizontal line is negative. Then sequentially measure the distance from the bifurcation point to the projection point of the lateral ankle tip on the plane on the sagittal plane image of the bifurcation point passing through the other branches as shown in Fig. 5. For the convenience of marking, the angle of the bifurcation point above the horizontal line is positive, and the angle below the horizontal line is negative.

Results

All the images (40/40) clearly showed the tibial nerve (TN) at the ankle canal and the bifurcation of the medial and lateral plantar nerves (MPN and LPN), with the gap of fat, the posterior tibial artery and vein besides the bifurcation. According to the position relationship between the medial and lateral plantar nerve bifurcation points, the projection of the horizontal line passing through the lowest point of the tip of the medial malleolus on the sagittal image (Line1) and the projection of the line connecting the tip of the medial malleolus and the calcaneus nodules on the sagittal image (Line2). the result can be divided into three types. ☒ type: 17 cases found in 40 cases(42.5%) of ankle tube proximal tibial bifurcation point is located, Line1 line above. ☒ type: bifurcation point is between Line1 and Line2, 23 cases (57.5%). ☒ type: bifurcation point is in Line2 far, we do not found this type of image. All of the above descriptions are shown in Fig. 6.

The reconstruction image of the medial and lateral plantar nerve is uniform in thickness and tapering from near to far, and the display range is obviously larger than that of the two at the same time, but when the two are displayed at the same time, the bifurcation position and morphology can be defined spe. The angle of medial and lateral plantar nerve is between 6°and 35°.

The occurrence rate of the medial calcaneal nerve (MCN) was 100%, though the number and starting position of the nerve varied greatly. Segmental reconstruction showed that the distal part of the nerve was located behind the calcaneal tuberosity and the subcutaneous tissue of the heel.Of the 40 images in our study, 18 had only one medial calcaneal nerve, 21 had two medial calcaneal nerves, and only one had three medial calcaneal nerves. From the position of origin, the medial calcaneal nerve can start from the tibial nerve, the plantar nerve, the lateral nerve bifurcation point and the lateral plantar nerve. No medial calcaneal nerve originating from the medial plantar nerve was found. Based on the MPR data, we divided the medial calcaneal nerve into the following major types, as shown in Fig. 7 and Fig. 8.

There were (38/40) cases in which the inferior calcaneal nerve (ICN) could be shown. In 32 cases, the inferior calcaneal nerve originated from the lateral plantar nerve. In 3 cases, the inferior calcaneal nerve originated from the bifurcation of the medial and lateral plantar nerves. In 3 cases, the inferior calcaneal

nerve originated from the tibial nerve. The origin locations were mainly shown in Fig. 9 and Fig. 10. In this group of images, 1 subcalcaneal nerve was reconstructed, and no more than 2 medial calcaneal nerve types were found. The starting point of the inferior calcaneal nerve is always located at the distal end of the starting point of the medial calcaneal nerve, and its endings are distributed in front of the calcaneal tuberosity and the abductor of the little toe as shown in Fig. 3C.

By measuring the distance to the projection point of the medial malleolus tip on the sagittal position of different bifurcation points and the included angle between the two lines and the projection on the plane through the horizontal line of the medial malleolus tip, each point can be marked inside of the ankle joint, as shown in Fig. 11.

Discussion

The ankle-canal is a narrow fibrous bone channel in anatomy, with tibial nerve and branches, posterior tibial blood vessels, and deep flexor tendon of the calf. The nerve channels in the ankle canal are divided into four septa by the fascia, and branches of the tibial nerve travel at different intervals [16]. These anatomical structures at the ankle canal are often related to many diseases, and the fine anatomy of the nerve in this area can be demonstrated morphologically by MR, which is of great significance for the diagnosis and clinical treatment of related diseases [15, 17].

The display of tibial nerve and branches at the ankle canal and their features on the 3D-FIESTA-C sequence.

At present, the MR research on peripheral nerve imaging mainly focuses on diffusion tensor imaging (DTI). However, DTI is susceptible to many factors of magnetic field and spatial and contrast resolution, and lacks the accuracy of evaluating small branches [18], so it is mainly applied to large nerves and branches. Further studies are needed to determine its role in daily clinical practice [19]. There are few studies on the nerve morphology of tibial nerve at the ankle canal with other MR sequences. Among them, Farooki et al. [14] preliminarily showed the inner and outer calcaneus nerves by using the orthogonal plane to conduct thin layer scan on the corpse, while Donovan [15] proposed that the inner and outer calcaneus nerves were more obvious in the oblique coronal plane. As the 3D-FIESTA-C sequence is encoded in 3D space, the inter-layer resolution of the 3D sequence is very high. A thin layer can ensure the isotropy of pixels, which is the basis for MR image to reconstruct high-quality images on any plane, and can clearly show relatively small nerve branches. Hatipoglu [20] applied this sequence to the study of posterior fossa nerve imaging. In the images of the 3D-FIESTA-C sequence, the nerve showed low signal, and between the muscle (slightly lower signal) and the tendon (lower signal), the peripheral fat showed high signal, and the blood vessels showed high signal and the thicker blood vessels showed low signal clipping sign. These are all necessary conditions to be able to show clear and distinguishable neural structures in multi-plane images. On the image of the transection of tibial nerve, although the tibial nerve presents low signal on the whole, multiple low-signal nerve fiber bundles and slightly higher signal intervals between the fiber bundles can be seen in it, and fat high signal can be seen around the tibial

nerve [21]. Note the accompanying posterior tibial artery and vein on the medial side of the nerve. With tibial nerve and its branches were strip structure and main longitudinal axis direction line along the human body, so most can through the oblique sagittal plane or oblique coronal plane reconstruction and shows a long range of neuromorphic to completely show nervous, not a plane can be two or three flat section reconstruction to display its full direction and form, and that multiple plane will not affect to the determination of the nervous (as shown in Fig. 3a, 3b, 3c, 3d).

The bifurcation position and branching pattern of the tibial nerve and branches at the ankle canal

The tibial nerve is generally cylindrical running behind and below the medial malleolus in the ankle canal, with two main branches: the medial plantar nerve and the lateral plantar nerve. Of course, Develi[22] reports a unique case of three branches, but this is very rare. The location of the distal branch of the tibial nerve is not constant. Bareither et al. [23] pointed out that the branch point can be within the range from 2.8 cm from the distal end of the medial malleolus tip to 14.3 cm from the proximal end. Dellon et al. [24] reported that the bifurcation point was within 2 cm of the malleolar-calcaneal axis. By dissecting 50 cases, Torres AL et AL. [9] found that 88% of them were located in the ankle canal and 12% in the proximal end of the ankle canal. In this study, medial plantar nerve and the lateral plantar nerve is divided into three types through positioning of the branch point, and 42.5% of bifurcation points now ankle tube proximal (type I), and bifurcation point is located in the ankle with 57.5% image tube (type II), ankle tube are not found in the remote far bifurcation point (type III), and Torres AL reported close to. In this study, the Angle between the inner and outer plantar nerves measured is between 6° and 35°, which is an acute angle less than 35°. The medial plantar nerve is one of the larger branches of the tibial nerve. It is located on the lateral side of the posterior tibial artery and in front of the medial plantar artery [17, 25]. The lateral plantar nerve is a smaller branch that runs between the inner and lateral plantar arteries [17]. The purpose of reconstructing the single branch of the inner and outer nerves of the plantar sole and displaying them at the maximum display level is to clearly observe their morphology, walking and whether there is compression on the pathway.

The medial calcaneal nerve is one of the main branches of the tibial nerve, terminating in the skin of the heel and the weight-bearing surface, and providing sensory innervation to the inner posterior side of the heel [26, 27]. The starting position and number of medial calcaneal nerves vary greatly. Quantitatively, Dellon[28] found that 37% had 1 medial calcaneal nerve, 41% had 2, 19% had 3, and 3% had 4. Kim [29] and Yang [10] found that there were up to 5 medial calcaneal nerves. Govsa [11] and Kim [29] indicate that the two most common vessels on the medial surface of the calcaneus are two. In this study, up to 3 medial calcaneal nerves were reconstructed, which may be related to small number of samples. However, two medial calcaneal nerves were the most reconstructed in this study, which is consistent with the above mentioned views. At the starting point, the medial calcaneal nerve may originate from the tibial nerve, the medial and lateral plantar nerve bifurcation points, and the lateral plantar nerve. Havel[30] and Dellon[28] found that the medial calcaneal nerve can also originate from the medial plantar nerve. These differences are mainly related to more than one calcaneal nerve in most cases, indicating the high rate of variation in the origin of the medial calcaneal nerve. Although the medial calcaneal nerve can originate from the tibial

nerve to the lateral plantar nerve, segmental reconstruction showed that its terminal branches showed a consistent range of innervation, all of which went to the heel skin behind the calcaneal tuberosity, which was consistent with anatomic conclusions [10, 11, 29, 31].

The inferior calcaneal nerve is also known as the first lateral plantar nerve, the little toe abductor nerve or the Baxter nerve [32–34]. Moroni[13], Oliva[35] and Govsa[11] all found that the occurrence rate of this nerve was 100%. In our reconstructed image, the display rate was 95%, and the anatomical data showed that the cross-sectional diameter at the beginning of the subcalcaneal nerve was (1.4 ± 0.5) mm. It is possible that the cases that weren't clearly shown are related to the fine nerve, which needs further study. The inferior calcaneal nerve always appears as a single branch, which was confirmed in our study, and no more than 2 medial calcaneal nerves were found. The origin position of the inferior calcaneal nerve is not constant. Arenson[37], Didia[31], Govsa[11] et al. believed that the inferior calcaneal nerve could originate from the lateral plantar nerve, the medial plantar nerve, the lateral nerve bifurcation and the tibial nerve, but our research results are consistent with Louisia[38] and Kim[39]. In all images, Most of the inferior calcaneal nerve originates from the lateral plantar nerve. In this study, we also found that the subcalcaneal nerve terminal shown by segmental reconstruction often disappeared in the muscular space or surrounding area in front of the tibial tubercle, and sometimes two branches could be reconstructed, with the anterior branch distributed in the area of the abductor muscle of the little toe and the posterior branch distributed in front of the calcaneal tubercle.

Clinical significance of positioning nerve bifurcation on body surface.

Ankle canal lesions, especially ankle canal syndrome, often requires minimally invasive interventional therapy or even surgical treatment [40]. During the surgical incision and route planning, positioning the nerve can avoid the nerve damage to the greatest extent, so that the patients can get better treatment effect and less complications. When using the external fixation of the fracture, positioning the nerve can also minimize the nerve damage. During nerve block, the effective injection site of ankle canal for heel pain can be determined by positioning the nerve [41]. In this study, we took the horizontal line passing through the medial malleolus tip as the reference line, and by measuring the distance from the bifurcation point to the medial malleolus tip and the included angle with the reference line, we could conveniently mark the body surface registration point of each point on the medial malleolus. This method can also be used to localize the lesion in the body surface and measure its depth by coronal position. These are of great significance for the invasive treatment of foot and ankle.

Conclusion

By applying MPR on the 3D-FIESTA-C sequence, the morphological description and classification of the nerve structure in the ankle canal were carried out in detail. By measuring the distance between each bifurcation point and the tip of the medial malleolus, and the angle between the line and the horizontal line passing the tip of the medial malleolus, the projection position of the bifurcation point on the body surface was marked. This method not only benefited the imaging diagnosis of tibial nerve and branch-

related lesions of the ankle canal, but also provided a good imaging basis to plan the clinical operation of the ankle canal and avoid surgical injury.

Abbreviations

3D-FIESTA-C: three-dimensional dual-excitation balanced steady-state free precession sequence;

MPR: multiplanar reconstruction; **TN:** tibial nerve; **MPN:** medial plantar nerve ; **LPN:** lateral plantar nerve; **MCN:** Medial calcaneal nerve; **LCN:** Inferior calcaneal nerve ; **QPM:** Square plantar muscle

Declarations

Ethics approval and consent to participate

Study was approved by the Feicheng Hospital of traditional Chinese Medicine of Shandong Province and Third Medical Centre of Chinese PLA General Hospital. An informed consent form was signed by each patient before the examination.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Author's Contributions

YZ and XH conceived the experiments. JY and WH performed the experiments. JL prepared the materials and laboratory. JZ retrieved regulatory and ethical approval for the study. SZ performed the data analysis. GW and XC supervised the work. All authors read and approved the final manuscript.

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Figures

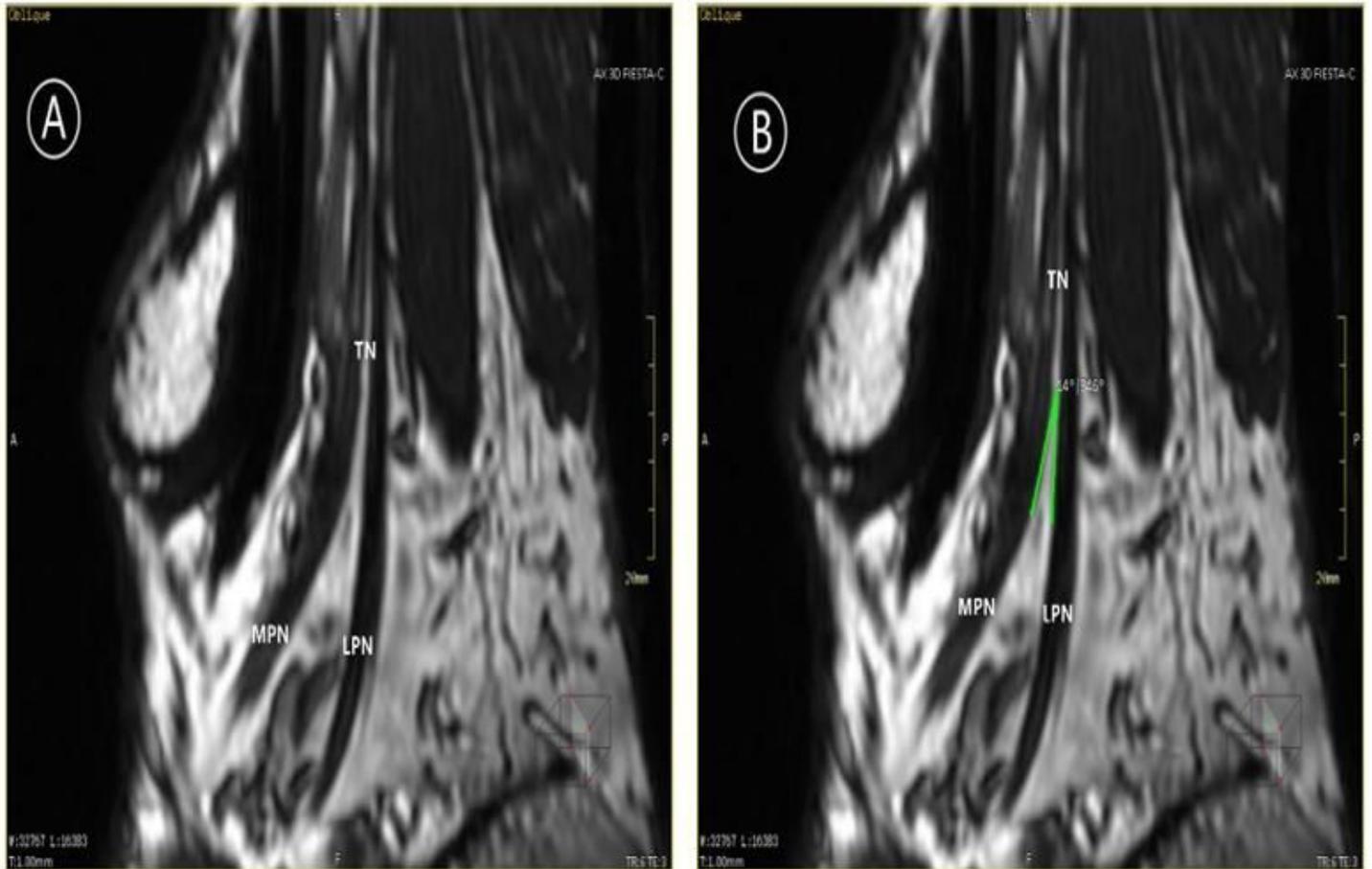


Figure 1

MPR shows the bifurcation of the medial and lateral plantar nerves at the same plane and bifurcation angle measurement: A the image of the oblique sagittal plane shows the bifurcation of the tibial nerve, the medial and lateral nerves of the plantar; B the angle between the medial and lateral nerves of the plantar can be measured on the oblique plane passing through the bifurcation of the tibial nerve.

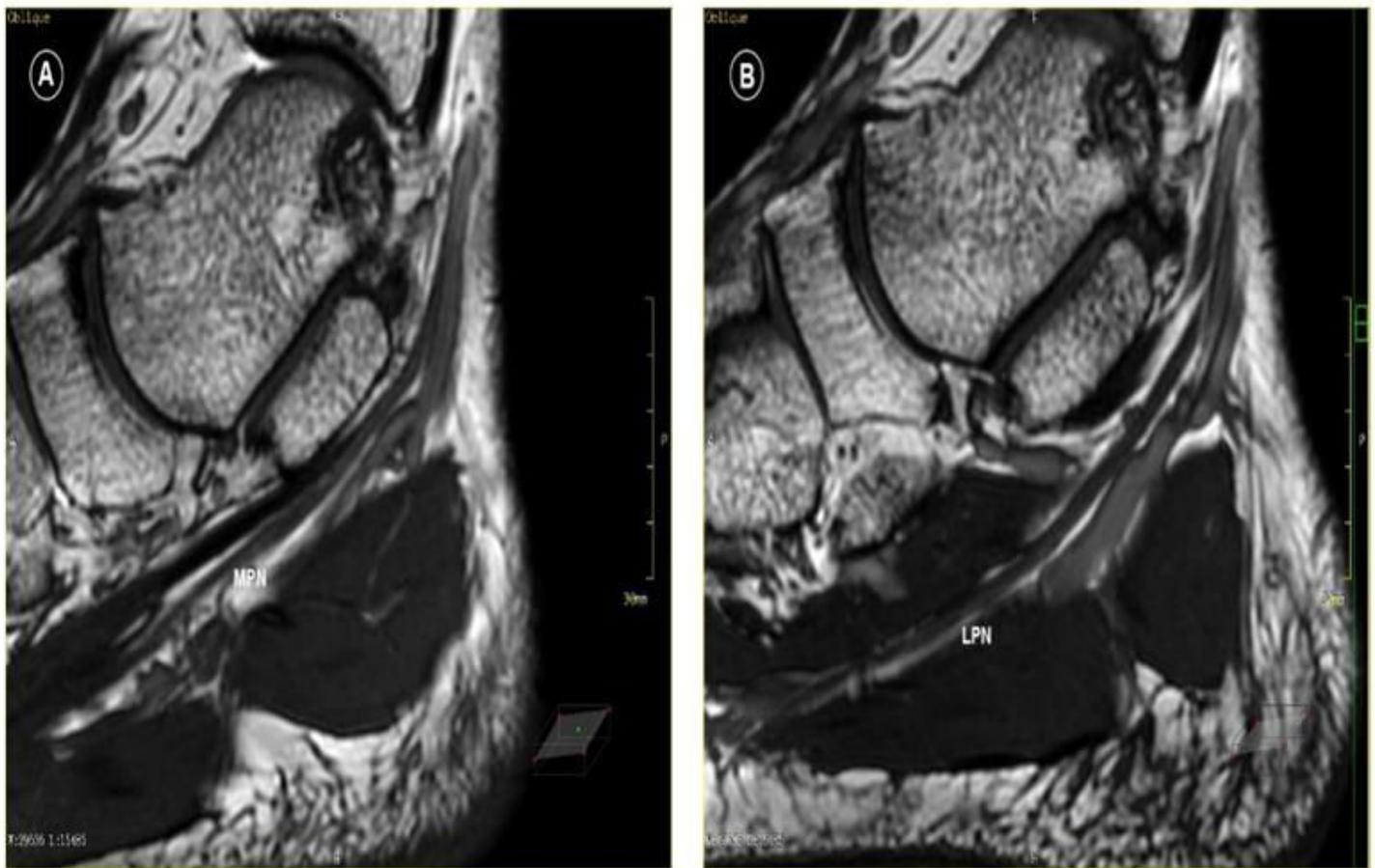


Figure 2

MPR shows images of medial and lateral plantar nerve: A the image of the oblique coronal plane that shows the medial plantar nerve in maximum range; B the image of the oblique coronal plane that shows the lateral plantar nerve in maximum range.

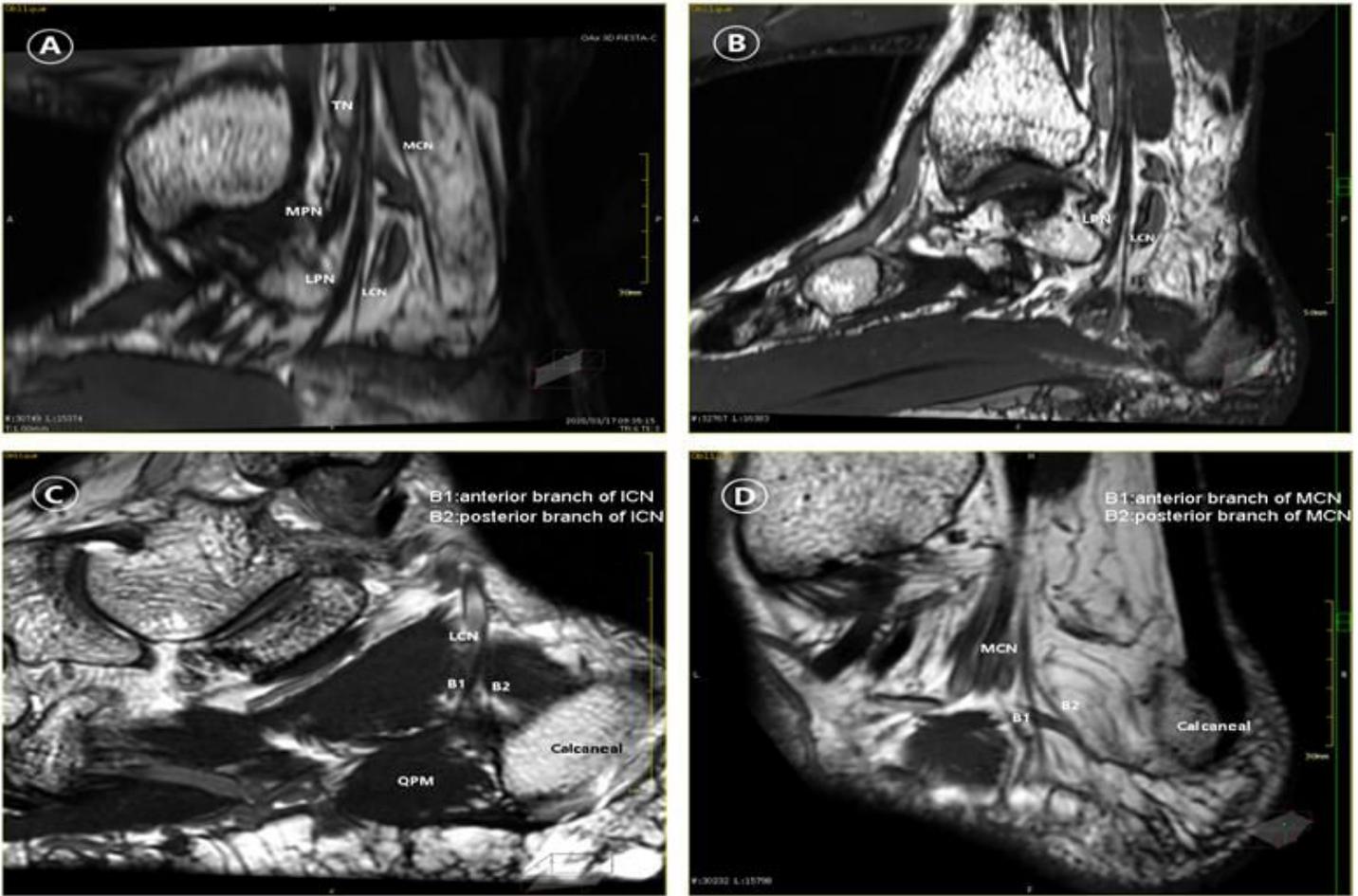


Figure 3

MPR shows the medial calcaneal nerve and the inferior calcaneal nerve: A the maximum extent of the medial calcaneal nerve is displayed on the oblique sagittal plane at the bifurcation of the medial calcaneal nerve; B the inferior calcaneal nerve is displayed on the oblique sagittal plane at the bifurcation of the inferior calcaneal nerve, which is emitted from the lateral plantar nerve; C the end of the inferior calcaneal nerve shown by the segmented reconstruction; D Segmental reconstruction of the medial calcaneal nerve ends.

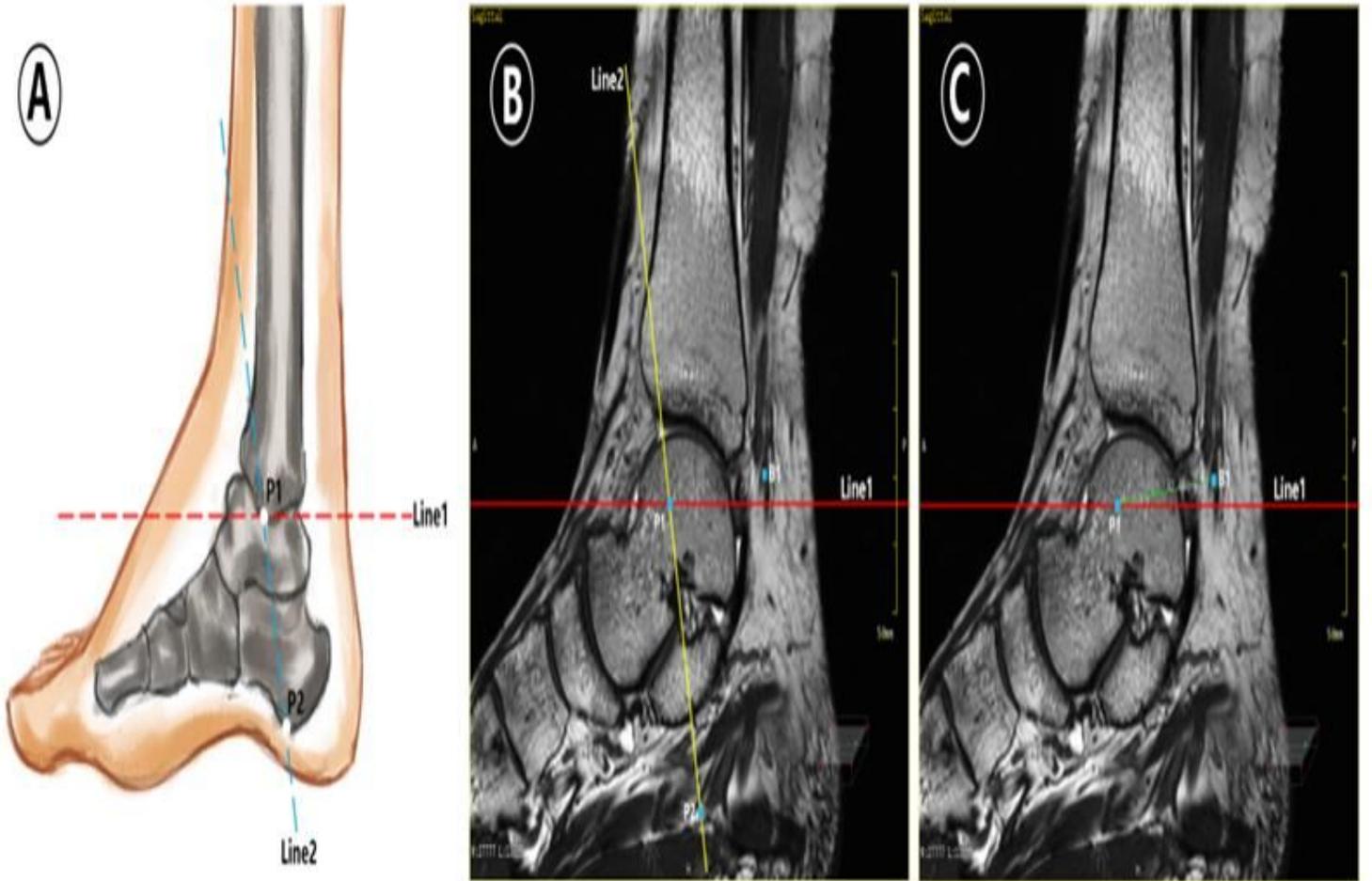


Figure 4

The relative position of the ankle canal reference line and the medial and lateral nerve: A a schematic diagram showing two projection lines, P1 is projection of the lowest point of the medial malleolus and P2 is projection of the calcaneal tuberosity on the sagittal image; B the relative position of the bifurcation point and Line1 and Line2 on the sagittal image through the bifurcation point of the medial and lateral nerves of the plantar; C measure the distance between the bifurcation point and P1 and the angle between the bifurcation point and Line1 on the sagittal image passing through the bifurcation points of the plantar and lateral nerves.

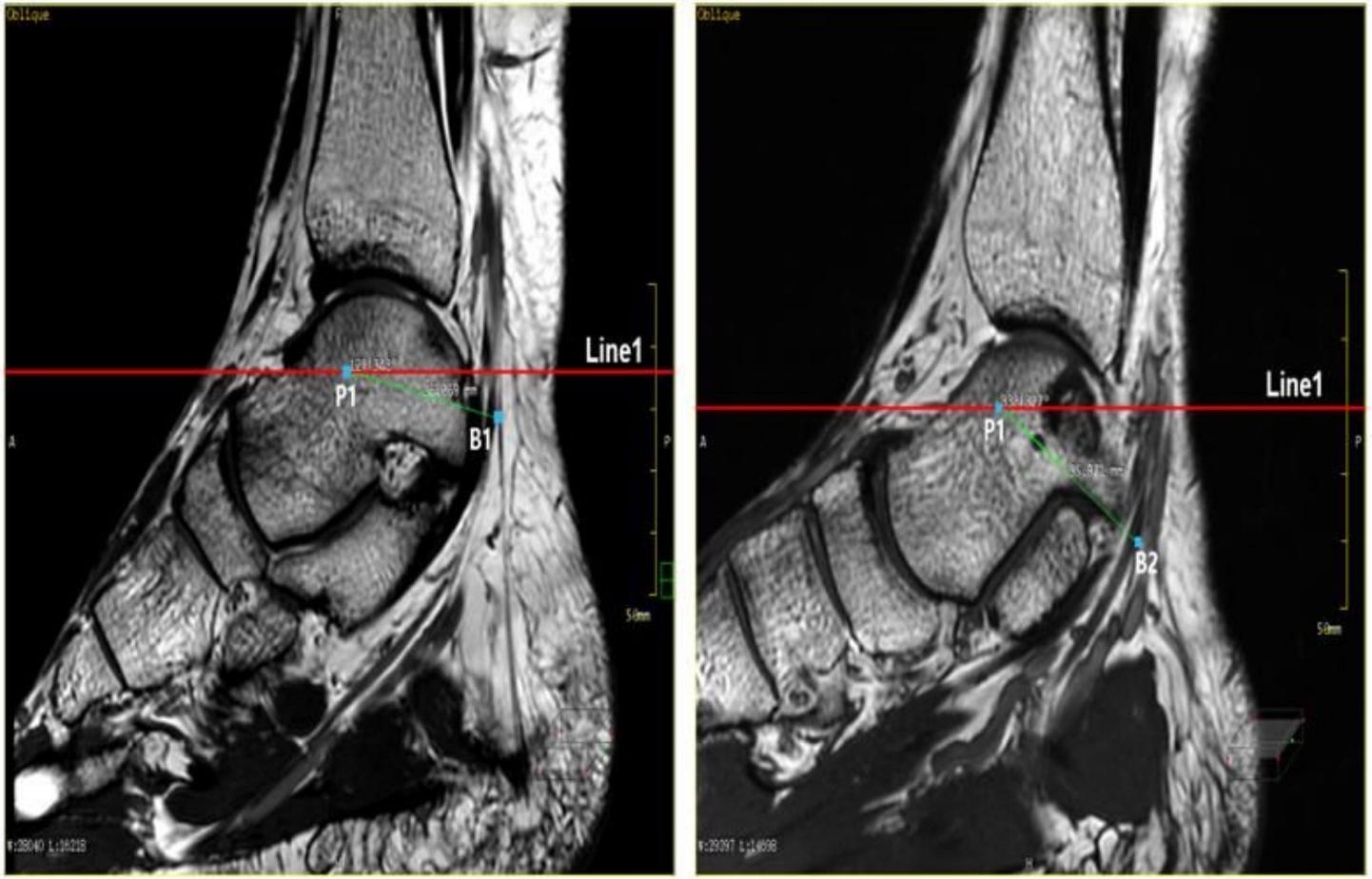


Figure 5

Measurement of the relative position of the medial and inferior calcaneal nerve on the sagittal plane: A measure the distance between the bifurcation point of MCN (B1) and projection of the lowest point of the medial malleolus (P1) and the angle between the bifurcation point and Line1; B the distance between the bifurcation point of ICN (B2) and P1, and the angle between the bifurcation point and Line1 are measured.

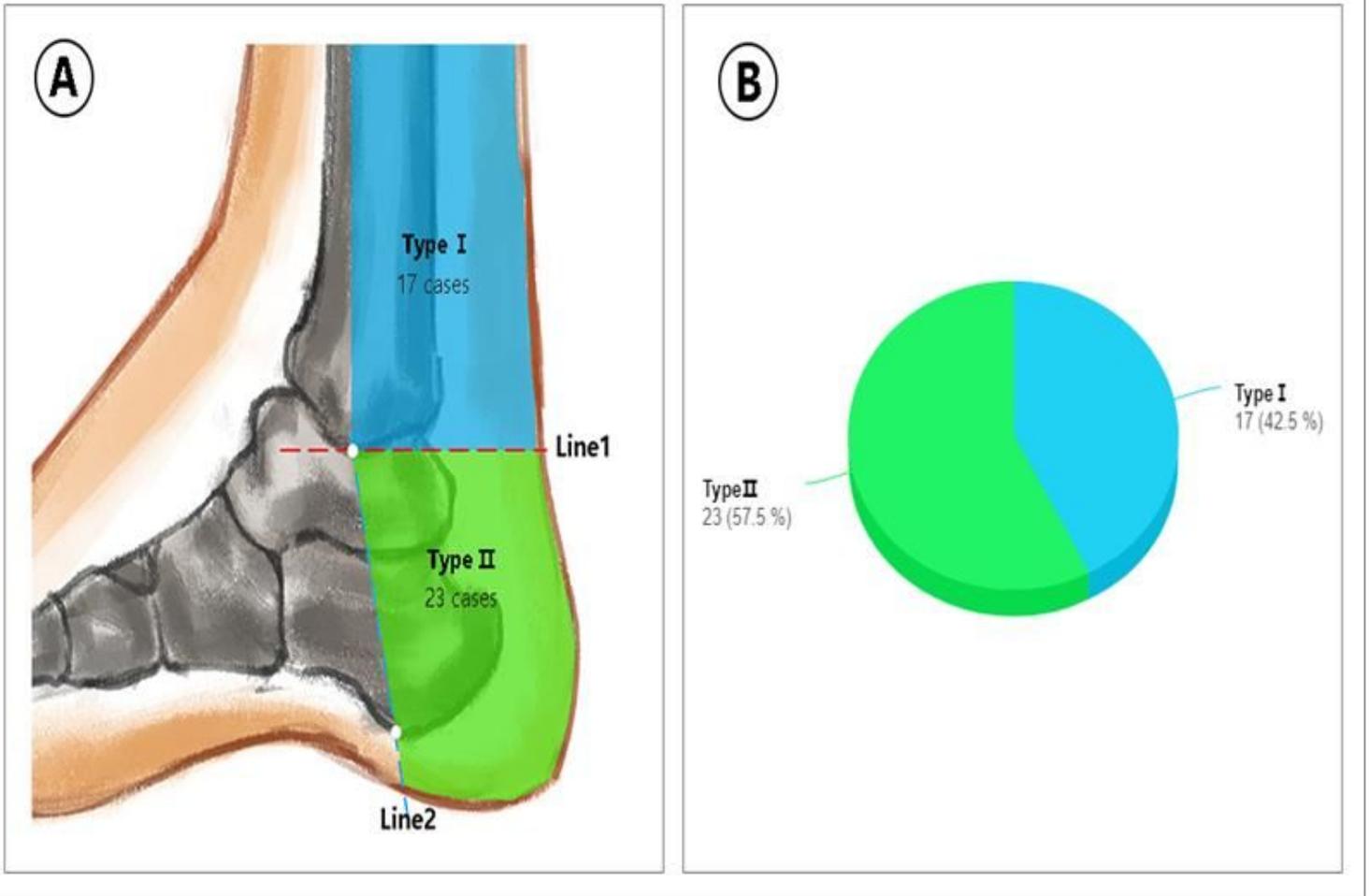


Figure 6

Types of the location of the bifurcation of the medial and lateral plantar nerves: A location illustration of the bifurcation points of the medial and lateral plantar nerves at the ankle canal. B scale diagram of the location of the bifurcation points of the medial and lateral plantar nerves.

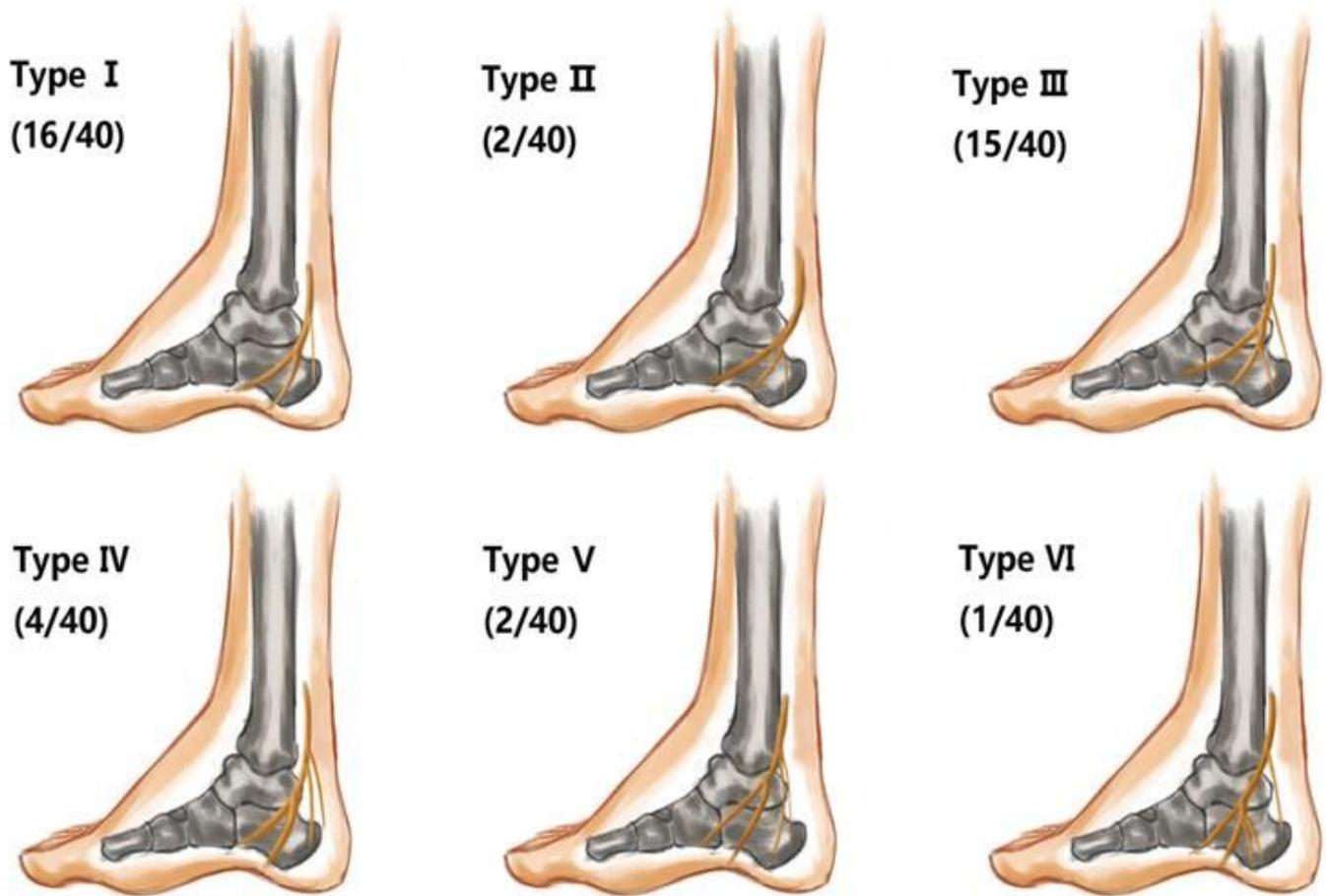


Figure 7

Modes of origins of the medial calcaneal nerve: Type I a medial calcaneal nerve originating from the tibial nerve; Type II a medial calcaneal nerve originating from the lateral plantar nerve; Type III two medial calcaneal nerves, one originated from the tibial nerve, and the other originated from lateral plantar nerve; Type IV two medial calcaneal nerves, both originated from tibial nerve; Type V two medial calcaneal nerves, with a common origin on the tibial nerve; Type VI three medial calcaneal nerves, one originated from the tibial nerve and the other two originated from the lateral plantar nerve.

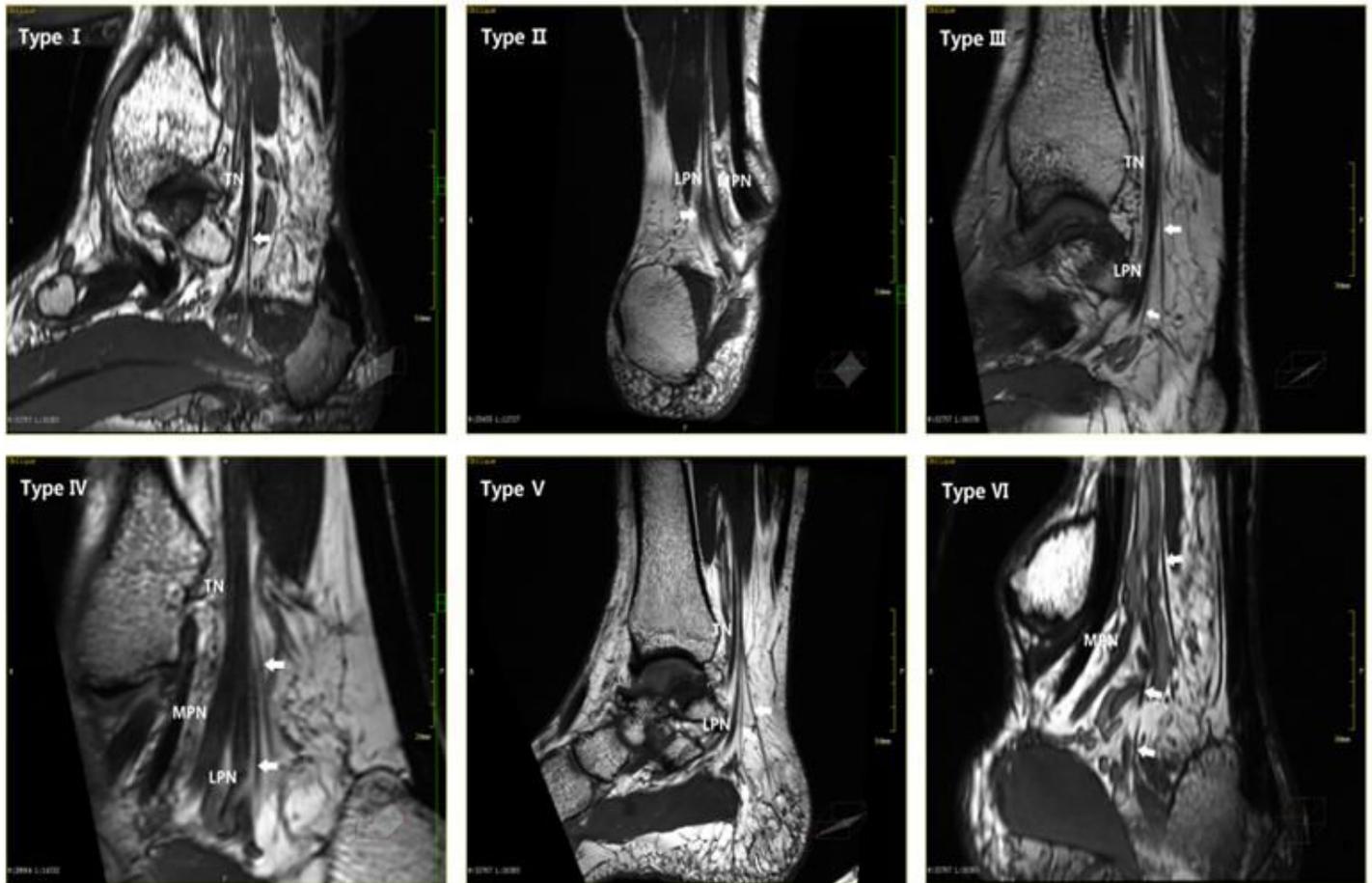


Figure 8

Reconstructed image of the medial nerve branch of the calcaneus (white arrow): MPR images of 6 types of the medial calcaneal nerve branches. Because the three nerves of type VI are not in the same plane, the MPR image cannot display their bifurcation points at the same plane.

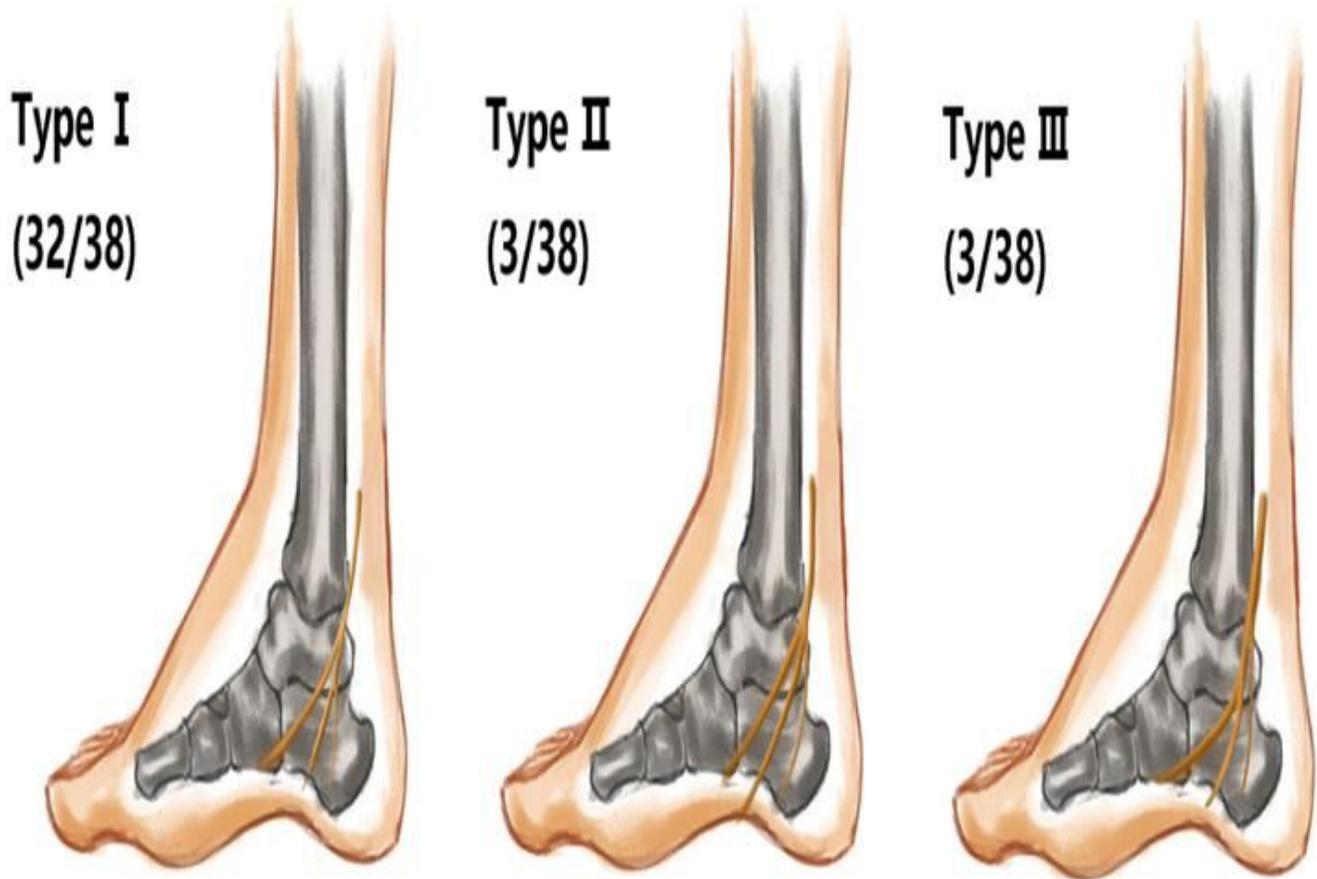


Figure 9

Modes of origins of the inferior calcaneal nerve: Type I the inferior calcaneal nerve originates from the tibial nerve; Type II the inferior calcaneal nerve originates from the bifurcation of the lateral plantar nerve; Type III the inferior calcaneal nerve originates from the tibial nerve.

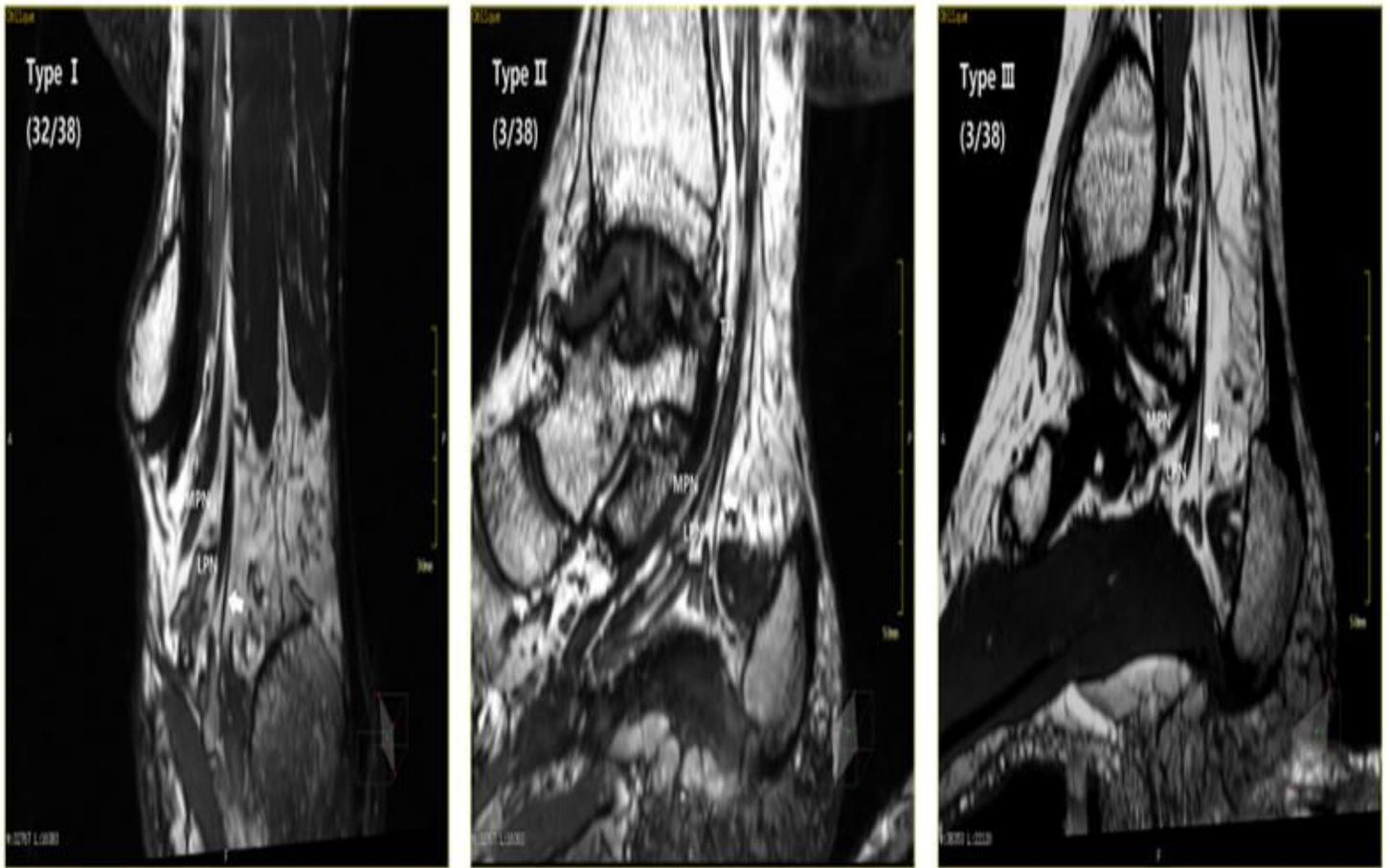


Figure 10

Reconstructed image of the inferior calcaneal nerve branches (white arrow): MPR images of 3 types of the inferior calcaneal nerve branches.

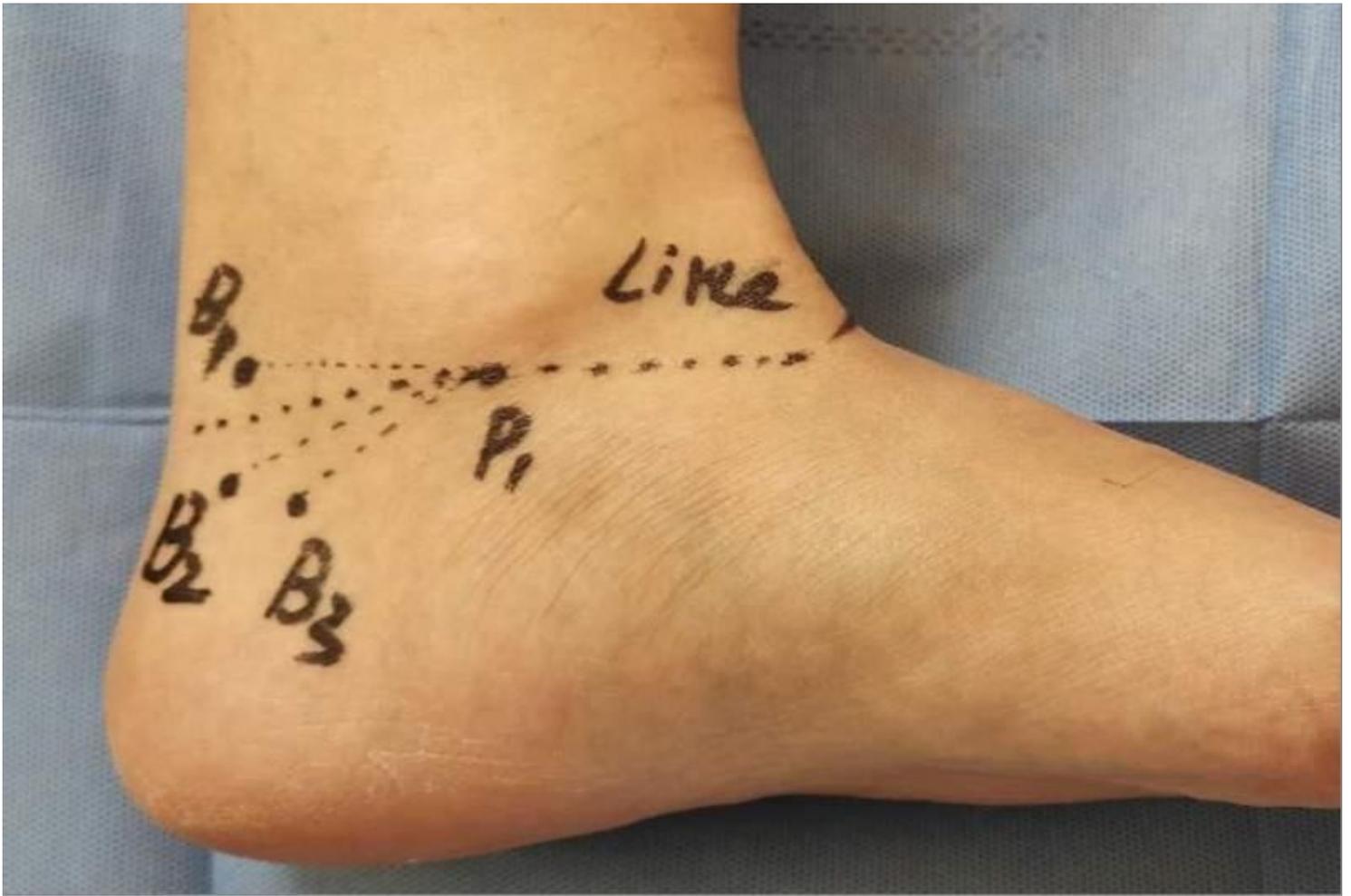


Figure 11

Projection point of the bifurcation point on the surface of the medial malleolus: The projection points of the projection of the bifurcation point of the medial and lateral nerves of the plantar (B1), the projection of the starting point of the medial calcaneal nerve (B2), the projection of the starting point of the inferior calcaneal nerve (B3) and the horizontal line passing through the lowest point of the tip of the medial malleolus (Line) can be marked on the surface of the inner ankle by measuring their positions.