Review paper

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Anatomical considerations of US-guided carpal tunnel release in daily clinical practice

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Keywords

carpal tunnel syndrome; carpal tunnel release; ultrasound; minimally invasive; vcarpal tunnel

Abstract

Carpal tunnel syndrome is the most frequent compression neuropathy with an incidence of one to three subjects per thousand. As specific anatomical variations might lead to unintended damage during surgical interventions, we present a review to elucidate the anatomical variability of the carpal tunnel region with important considerations for daily clinical practice: several variants of the median nerve branches in and around the transverse carpal ligament are typical and must – similarly to the variant courses of the median artery, which may be found eccentric ulnar to the median nerve – be taken into account in any interventional therapy at the carpal tunnel. Unintended interference in these structures might lead to heavy arterial bleeding and, in consequence, even underperfusion of segments of the median nerve or, if neural structures such as variant nerve branches are impaired or even cut, severe pain-syndromes with a profound impact on the quality of life. This knowledge is thus crucial for outcome- and safety-optimization of different surgical procedures at the volar aspect of the wrist and surgical therapy of the carpal tunnel syndrome e.g., US-guided carpal tunnel release, as injury might result in dysfunction and/or pain on wrist motion or direct impact in the region concerned. For most variations, anatomical and surgical descriptions vary, as official classifications are still lacking.

Introduction

Carpal tunnel syndrome (CTS) is the most frequent compression neuropathy with a reported prevalence of one to three subjects per thousand[(1)]. Symptoms are typical, and the diagnosis can be further supported by electrophysiological tests and high-resolution ultrasound (HRUS)[(1–3)]. Although conservative treatment options such as splinting, physiotherapy and steroid applications are widely used, only surgical procedures with complete transection of the flexor retinaculum (FLR) result in reliable long-term improvement[(4–6)].

Beside open carpal tunnel release (CTR) and endoscopic procedures, minimally invasive procedures in various anatomical regions including the tarsal and carpal tunnel have attracted attention, as they are associated with little tissue trauma and are less invasive, thus producing fewer side-effects[(7–15)]. Petrover *et al.* demonstrated the safety and efficacy of minimally invasive HRUS-guided CTR[(16,17)]. A modified HRUS-guided CTR was also described by Loizides *et al.* using an additional blunt button tip cannula with several advantages: it allows for stump splinting of the carpal tunnel (CT), serves as a track for the subsequent insertion of the hook knife, and serves as a protection device between the median nerve (MN) and the hook knife. It can additionally be used to hydro-inflate the CT at any time, if needed[(18)].

In any variant of the CTR-procedure, a profound anatomical knowledge of the wrist region is fundamental. Especially in HRUS-guided CTR, the initial evaluation of the US-anatomy of the CT is obligatory, as the boundaries and variations of the working space must be known and thoroughly defined prior to intervention. In this context, the MN and its branches should be evaluated with a focus on specific anatomical variants, as they might lead to unintended damage and (postoperative) complications.

Therefore, we hereby present considerations and important anatomical variations of the MN that are relevant to minimally invasive HRUS-guided CTR procedures in daily clinical practice.

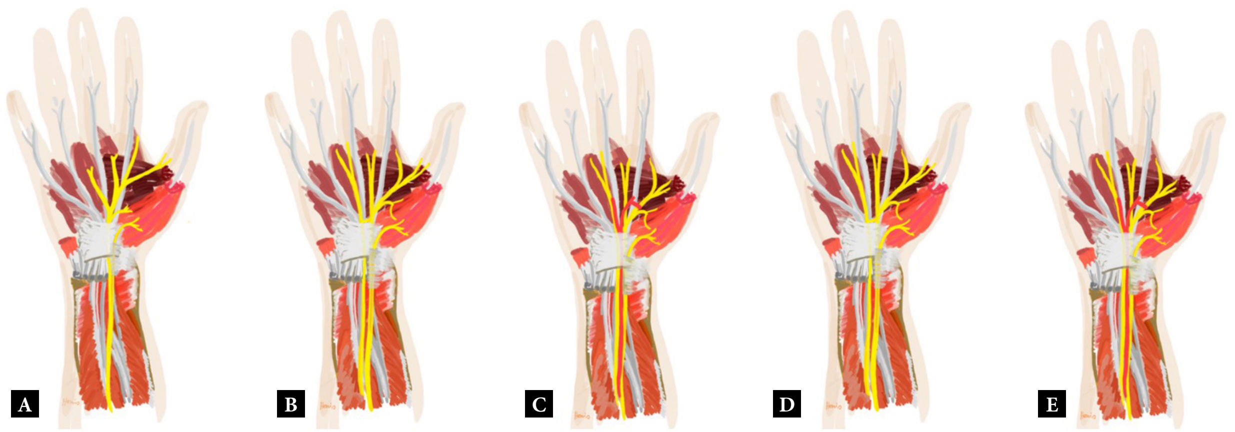

Fig. 1. *Anatomical variations of the MN: Single MN (**A**), bifid MN (**B**), bifid MN with PMA (**C**), bifid MN in separate compartments (**D**), trifid MN (**E**)*

Normal anatomy of the median nerve

The MN is formed by the union of the lateral and medial roots from the respective brachial plexus chords within the axillary fossa. It runs downwards through the medial bicipital groove and the cubital fossa. At the level of the cubital fossa, the MN runs between the two heads of the pronator teres, a region for an admittedly rare compression neuropathy, directly deep to the bicipital aponeurosis (lacertus fibrosus). In the forearm, the MN first runs between the superficial and deep flexor digitorum muscles, rises radially to the muscle tendons, and enters the CT directly deep to the FLR, slightly radial to the midline[19] (Fig. 1 A).

Normal anatomy of the carpal tunnel

The CT is an open compartment containing nine flexor tendons and the MN, framed by the carpal bones and the FLR. The FLR is attached radially to the scaphoid and the trapezium tubercle (eminentia carpalis radialis) and ulnarly to the triquetrum bone and the hook of hamate (eminentia carpalis ulnaris)[20,21]. By definition, the FLR is not a transverse ligament but a retinaculum[22]. The structure and quality of the FLR are notable factors for the mechanical characteristics of the CT[23,24], given that changes to its thickness or stiffness may directly correlate to CTS[23,25–29] (Fig. 2). Additionally, the thenar muscles originating at the palmar surface of the FLR have an impact on the biomechanics of the CT[30] as well as the lumbricals which slip into the CT during flexion of the finger[31,32]. The width of the CT is at its narrowest about two centimeters from its proximal margin, which is at the level of the hook of hamate. However, strength of pressure within the CT varies significantly between the proximal and distal parts depending on hand posture[33–36]. Excessive pressure within the CT leads to local compression of the vasa nervorum of the MN, resulting in MN ischemia. Additionally, the MN itself can be mechanically compressed[30,33,37,38]. In CTS, both ischemia and long-lasting compression of the MN cause neuropathy, characterized by swelling of the nerve proximal to the FLR and flattening at the level of entrapment[30,39,40].

According to the literature, within the CT, the MN always lies superficial to the flexor tendons. A position profound to the deep flexor tendons or between the superficial and deep flexor tendons has not as yet been documented (Fig. 3).

Variability of anatomy of the carpal tunnel

Normally, no vessels pass through the CT. Nevertheless, the persistent median artery (PMA) can accompany the MN within the CT. It is a small artery that usually regresses after the eighth week of intrauterine life but in some cases persists into adulthood[41]. There are two patterns of PMA reported; one antebrachial pattern that neither reaches the CT nor the palm, and one palmar pattern, which passes through the CT to the palm[42]. The incidence of the palmar PMA has been reported as 4%[43], 11.5%[44] to 20%[45], and is mostly unilateral[41,43,45]. It is associated with variations in MN anatomy[44,46], with CTS[43,46,47], and can be a valuable landmark when repairing the transected nerve[19,41,48]. The typical origin of the palmar PMA is either the ulnar artery or the anterior interosseous

Fig. 2. *Opened CT: Note the thickness and width of the FLR (tweezers)*

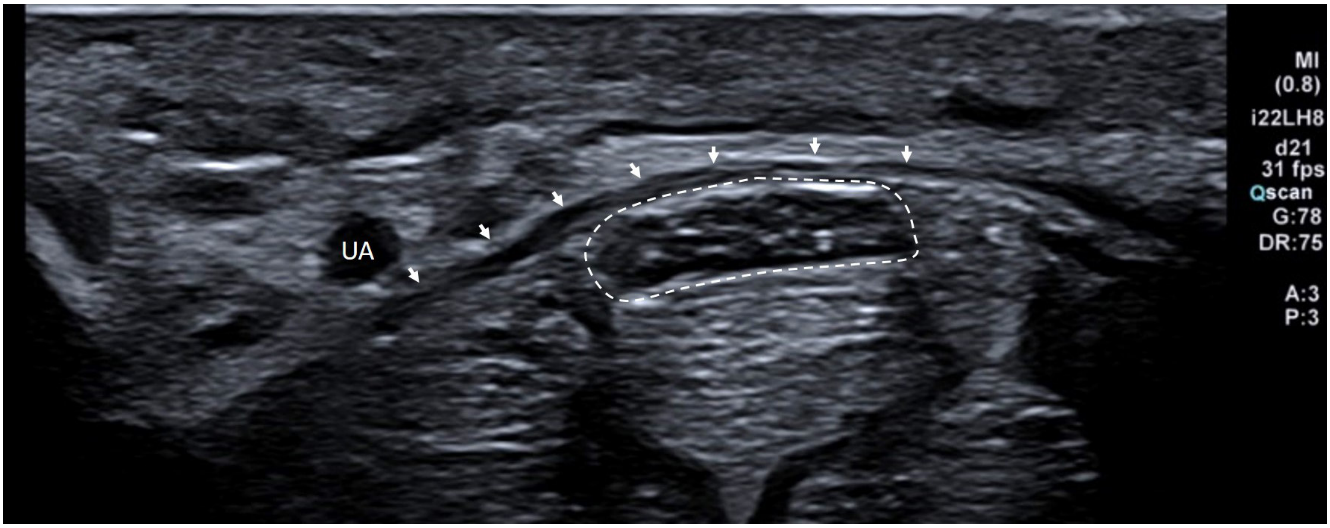

Fig. 3. *Normal MN (dotted line) at the level of the FLR (arrows)*

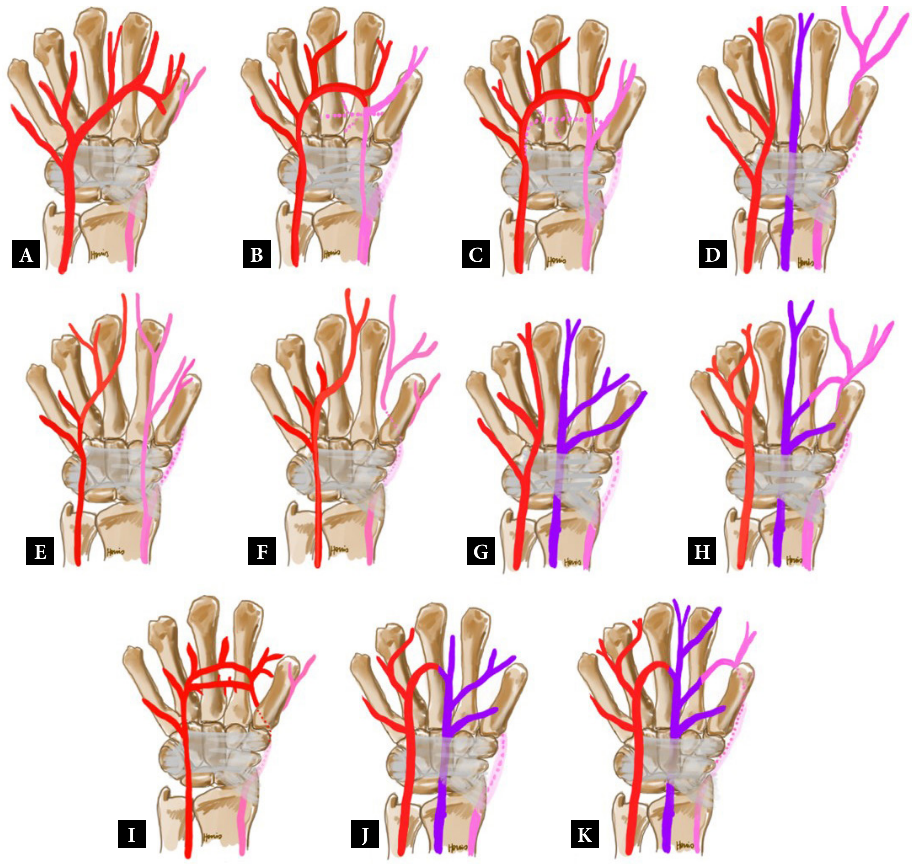

Fig. 4. *Anatomical variations of the palmar arteries: UA (red), PMA (purple), RA (pink). Complete arch coming from the UA (***A***), complete arch coming from the UA + superficial palmar branch of RA (***B***), two complete arches (superficial and deep) from the UA and superficial palmar branch of RA connected with the deep palmar branch of RA (***C***), no arch with separate UA, PMA and RA (***D***), no arch with separate UA and superficial palmar branch of RA (***E***), no arch with separate UA and RA (***F***), no arch with separate UA and PMA (***G***), incomplete arch from the RA + PMA with separate UA (***H***), double arch from the UA + RA (***I***), complete arch from the UA + PMA (***J***), two complete arches from the UA+PMA and PMA+RA (K)*

artery[49]. At the palm, the palmar PMA can either connect with both the radial and ulnar arteries, connect with only one of them, or independently supply the palmar digital arteries (mainly on the radial side)[49]. A summary of the anatomical variations of palmar arteries is shown in Fig. 4. Anatomical photographs show examples of PMA variations in Fig. 5 and Fig. 6. On US, an example of a double superficial palmar arch with looping of the distal portion is visualized (Fig. 7).

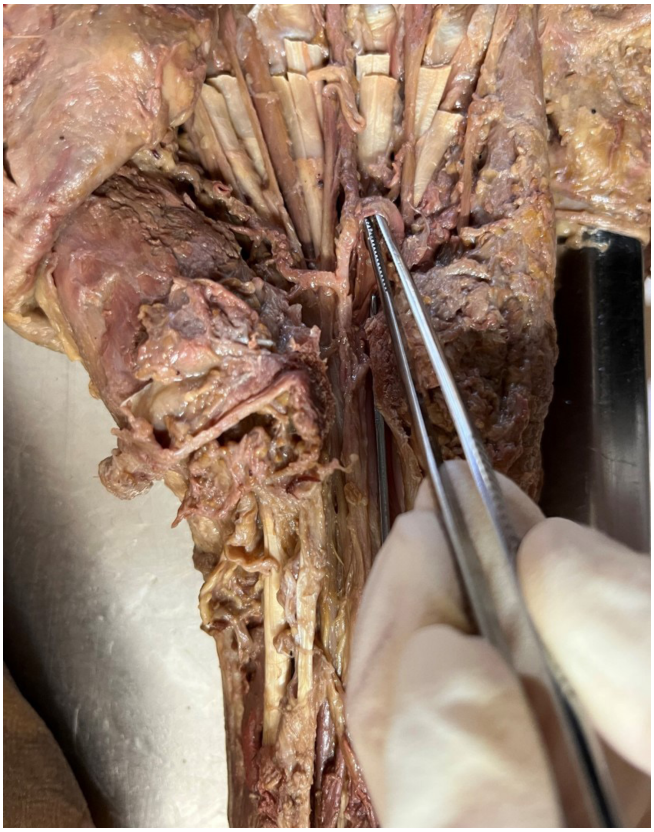

Fig. 5. *Proximal superficial palmar arch from the UA and PMA, mobilized by tweezers*

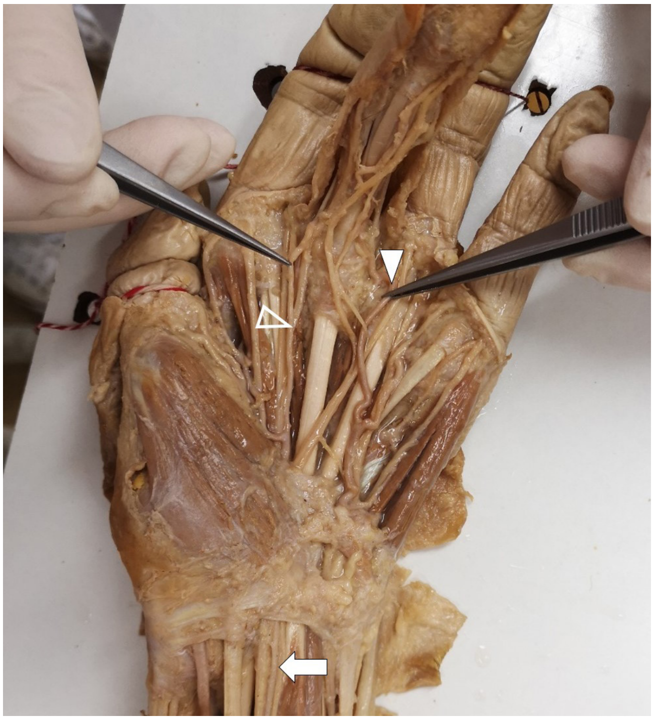

Fig. 6. *Missing superficial palmar arch with separate PMA (arrow proximal and void arrow distal) supplying the index and radial middle fingers, next to the UA (full arrowhead) supplying the ulnar middle finger, ring finger, and small finger*

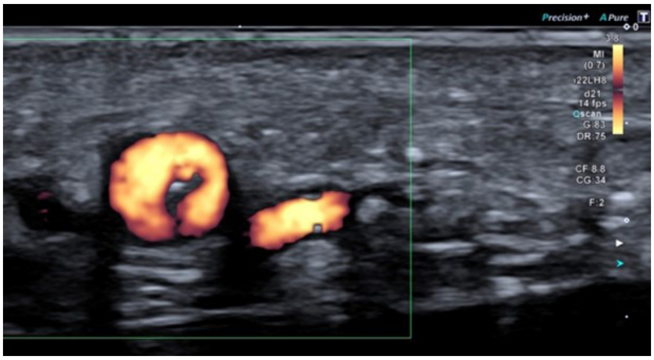

Fig. 7. *Double superficial palmar arch with looping of the distal portion*

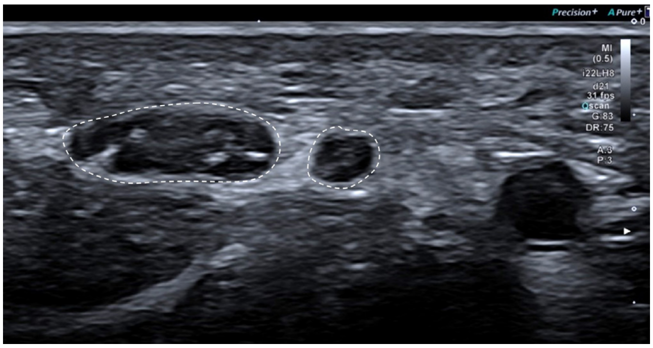

Fig. 8. *US image depicting two portions of a bifid MN (dotted line) in a patient with CTS. Note the enlarged and hypoechogenic MN-portions*

There are bifid or even trifid variations of the MN (Fig. 1 B–E). According to Lanz, a proximal division of the MN is found in only 0.8% of cases[50], whereas in other studies this variation has been reported to occur in 2%[51,52], 2.8%[53–55], 9.4%[56] or 11.5%[44] of cases, e.g. visualized by US in Fig. 8. A bifid MN is associated with various clinically relevant variations such as accessory muscles, palmar PMA, and an increased risk of CTS[53,54,57–59]. Within bifid or trifid MN variations, the prevalence of palmar PMA is more than 60%[55], e.g. shown in the US image of an asymptomatic trifid MN variation with PMA (Fig. 9). Szabo *et al*. described the variation of a bifid MN that runs in separated ligamentous tunnels, connected by an accessory branch located above the MN trunk, which could be misinterpreted as the thenar motor branch of the median nerve (TMB)[60].

The MN course into the CT is straight in two thirds of cases or curved in one third. In a straight course, it lies radially to the midline in 43%, in the midline of CT in 22%, and ulnarly in less than 2%. In a curved course, it shifts within the CT to the radial side in 21%, to the ulnar side in 12% of cases[61].

Accessory muscles or variations of tendinous interconnections within the CT occur in up to 60%[62] of cases, more commonly unilaterally[63]. The lumbricals may originate more proximally[64,65], flexors of the fingers, thenar muscles or the palmaris longus may show variability in the number of fascicles, heads, origin, and insertion[62,63,66–70]. Accessory muscles are rarely the main cause of CTS but may increase the risk of iatrogenic injury due to ectopic motor branches[33,34,47,62,66,67,70,71].

The palmar branch of the UN, which occurs in less than 50% of cases, may lie near the incision line for CTR in 12.5% of patients[72].

Fig. 9. *US image depicting three portions of a trifid MN (dotted lines) and PMA in an asymptomatic patient*

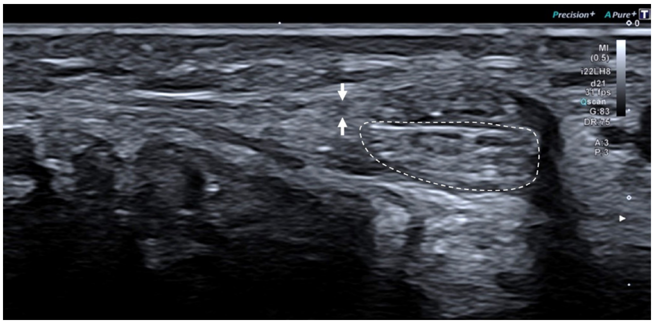

Fig. 11. *Normal PBMN (arrows) radial to the MN (dotted line)*

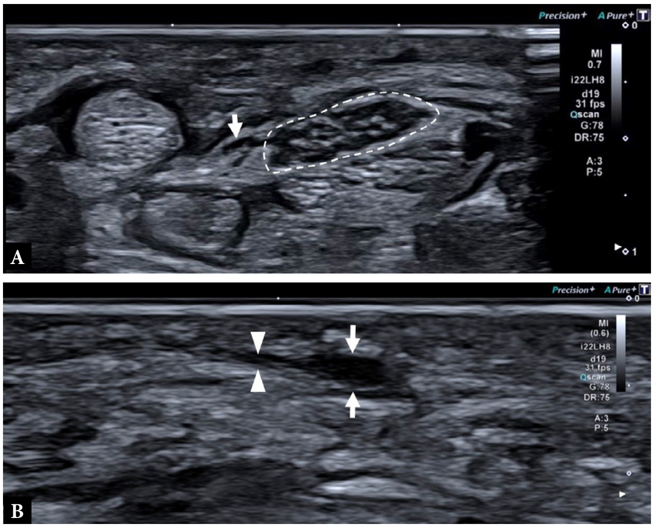

Fig. 12. *Transverse (***A***) and longitudinal (***B***) US image depicting the MN (dotted line) and a neuroma (arrows) of the PBMN (arrowheads)*

Branches of the median nerve

The MN gives off a slim palmar branch (PBMN) which typically arises from the radial side of the nerve, about five centimeters proximal to the distal flexion crease of the wrist (Fig. 10 A, Fig. 11). After its origin, the PBMN crosses deep to and then medially to the tendon of the flexor carpi radialis. While the MN runs deep to the FLR, the PBMN runs superficial to it, deep to the lateral part of the palmaris longus (when present). It emerges superficial to the antebrachial fascia within 1.5 cm of the wrist crease[73]. The emerging point is associated with the distal end of the tendon of palmaris longus or its terminal fibers. The PBMN gives sensory innervation to the volar part of the hand and small fibers down through the palmar aponeurosis terminating in the FLR. Iatrogenic injury of small fibers of the PBMN may be one of the causes of postoperative dysesthesia[73–75], e.g., shown in the US images of a neuroma of the PBMN in a patient with volar wrist and hand pain (Fig. 12).

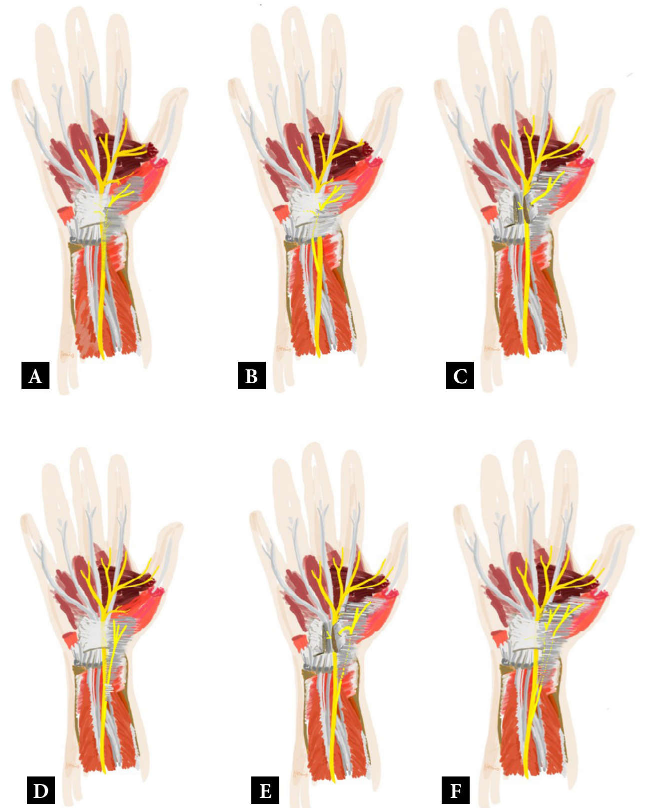

Fig. 10. *Anatomical variations of the PBMN (straw yellow): Normal PBMN running superficial to the FLR (***A***), ulnar origin of PBMN (***B***), PBMN piercing the FLR (***C***), PBMN perforating the antebrachial fascia very proximal (***D***), PBMN piercing the antebrachial fascia prior to separating into its superficial and deep branches, deep branches pierce the FLR (***E***), double PBMN (***F***)*

The MN itself divides at the distal margin of the CT into ulnar and radial portions, containing sensory and motor fibers. These portions divide into the common palmar digital nerves (CPDNs), ending up in proper palmar digital nerves (PPDNs). The ulnar portion gives off the CPDN, which innervates the second lumbrical and terminates in the PPDN of the ulnar side of the middle finger and the radial side of the ring finger. The radial portion gives off two CPDNs, with the first one typically trifurcating, the second one bifurcating, as well as the TMB (Fig. 13, Fig. 14). The radial CPDN of the radial portion gives off PPDNs to the thumb and the radial side of the index finger as well as the nerve to the first lumbrical. The ulnar CPDN of the radial portion gives off the PPDN to the ulnar side of the index finger and the radial side of the middle finger. At the thenar eminence, MN innervates the abductor pollicis brevis, the opponens pollicis, and the superficial head of the flexor pollicis brevis (FPB) muscles, while deep branches of the ulnar nerve (UN) innervate the deep head of the FPB and the adductor pollicis. In most cases, the tendon of the flexor pollicis longus (FPL) marks the division line

Fig. 13. *TMB (arrowhead) arising typically from the radial aspect of the MN (arrows)*

Fig. 15. *PBMN (arrows) piercing the FLR (arrowhead)*

between the muscles innervated by the MN and those innervated by the UN[48,75,76].

Variability of the palmar branch of median nerve

The prevalence of the PBMN is over 90%[72,77]. In its absence, other nerve branches has to replace its sensory innervation area, e.g., the palmar branch of ulnar nerve. Variations of the PBMN, pictured in

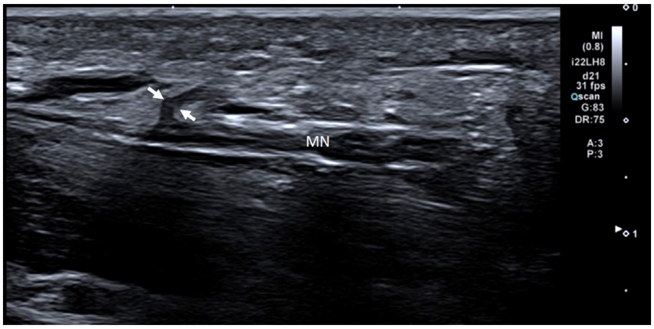

Fig. 14. *US image in longitudinal direction, depicting the MN and the "recurrent" course of the TMB (arrows)*

Fig. 10 B–F, are of clinical importance, as harm may result in dysesthesia and pain on wrist extension[55,73,78]. The course of the PBMN often varies when comparing both sides[77].

The PBMN may originate from the ulnar side of the MN[58] or in other cases it may have its origin with two strands[73,79,80]. At the thenar eminence, PBMN splits into two, three or rarely into multiple branches[73]. It can either only divide into its superficial branches or also give off a deep branch. Motor fibers to the thenar muscles may occur as a rare anatomical variant[73].

Typically, the PBMN lies superficial to the FLR, and only pierces the antebrachial fascia, but there are cases where it follows the MN far distally and pierces the FLR prior to becoming epifascial (Fig. 15). Also, the PBMN can pierce through the antebrachial fascia very proximal, then stay subcutaneously[81]. A duplicated PBMN may follow the MN with one part and form a loop with the other part through the FLR[73,75]. In addition, a loop can be formed between the deep and superficial branches of the PBMN[75] or between the PBMN and a superficial branch of the radial nerve[75,82].

Variability of the thenar motor branch

In clinical practice, variations of the MN within the CT are classified by Lanz[50], although Poisel[83] proposed a classification system three years earlier. While Poisel distinguished variations of the course of one TMB depending on its relation to the FLR, the Lanz classification divides the anatomical situation of the MN into four types. Thereby, three types refer to one single MN, specified by the course of the TMB including accessory branches, and one type refers to a divided MN trunk inside the CT. Subtypes are used to specify the details.

In Type 1 (Fig. 16 A–E), occurring in the majority of cases 83%[55], 84%[44], 88%[50], Lanz includes all types of Poisel, who distinguished an extraligamentous, a subligamentous, and a transligamentous type. Poisel's extraligamentous Lanz 1 is the most common anatomical variant with a prevalence between 40 and 97%[50,55,83–87]. A high heterogeneity is found in the literature, e.g., Agarwal *et al.* (India, 52 hands) documented the transligamentous course more often than the extraligamentous one (42.3% transligamentous vs. 36.5% extraligamentous)[44], whereas Raviprasanna *et al.* (India, 51 hands) documented the extraligamenous course more often (79% extraligamentous vs. 2% transligamentous)[88]. However, there are no significant differences in the pooled prevalence[55].

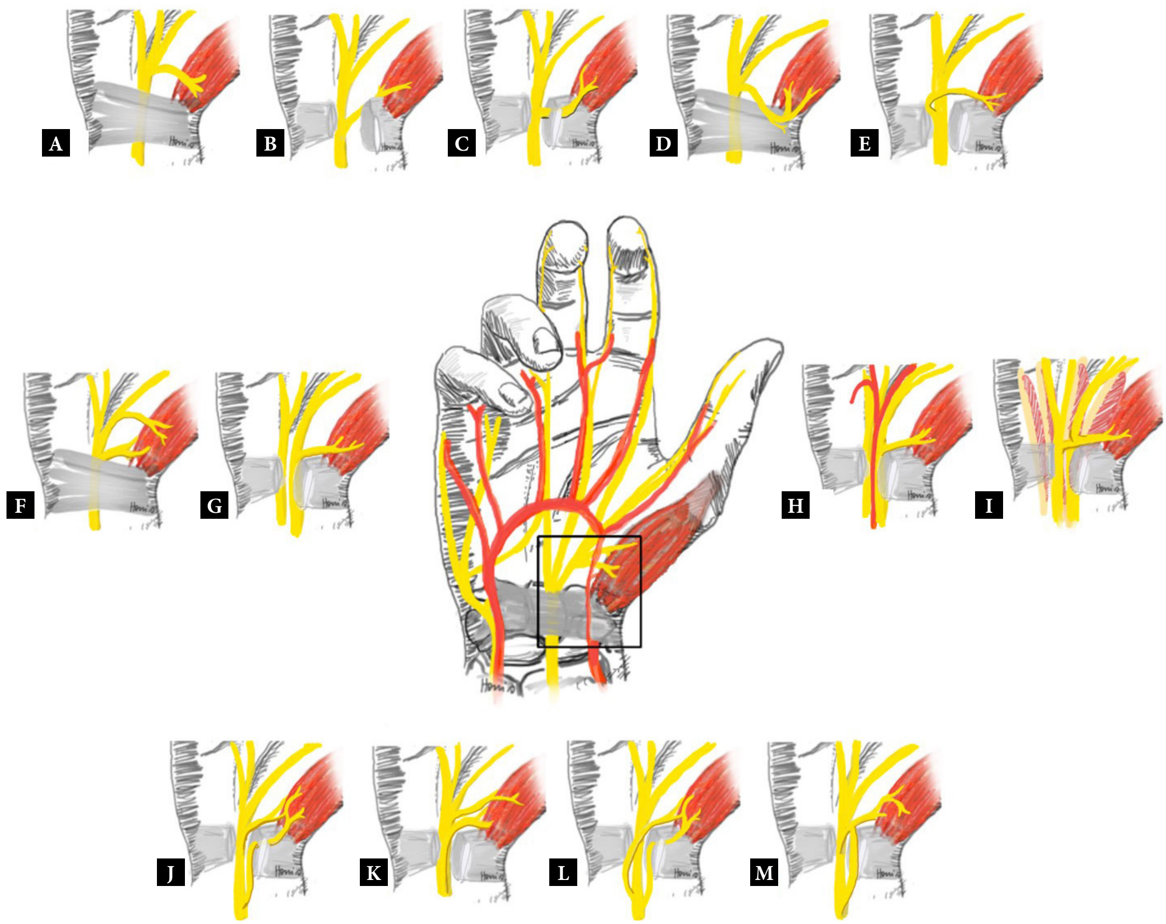

Fig. 16. *Anatomical variations of the TMB: distal extraligamentous single TMB (***A***), subligamentous single TMB (***B***), transligamentous single TMB (***C***), supraligamentous single TMB (***D***), from ulnar side of MN originating single TMB (***E***), TMB with additional distal accessory branch (***F***), single (or double) TMB coming from a bifid MN (***G***), single (or double) TMB coming from a bifid MN accompanied by the PMA (***H***), single (or double) TMB coming from a bifid MN besides thick lumbrical muscles (***I***), TMB with an additional proximal accessory branch piercing the FLR (***J***), TMB with an additional proximal accessory TMB escorting the MN through CT (***K***), two TMBs originating both from the radial and ulnar sides of MN (***L***), TMB with communicating additional proximal accessory branch (***M***)*

The TMB comes from the ulnar side of the MN in 2–3% of cases[55,84] (Fig. 17). Besides, some authors describe a supraligamentous variation of the TMB, viz. The TMB originates from the palmar or ulnar side of the MN within the CT, then traverses upon the palmar surface of the retinaculum to reach the thenar muscles[89,90]. Case studies also describe a preligamentous course of the TMB, assessing a variation where the TMB departs proximal to the CT, not passing through it but running superficial to the FLR[86,91].

The muscles overlying the FLR, occurring in 9%[92] to 13%[93], are associated with a TMB that courses from the radial to the ulnar side superficial to the FLR[93]. Hypertrophic thenar muscles are more common in cases with a transligamentous course of the TMB[44,86,94] and may be associated with a higher risk of CTS[95].

Lanz Type 2 (Fig. 16 F) includes accessory motor branches at the distal portion of the FLR, occurring in less than 5% of patients[55].

Lanz Type 3 (Fig. 16 G–I) includes all forms of the separated MN within the CT. Subtypes distinguish between cases with or without the palmar PMA or the lumbricals. The proximal divided MN may occur with multiple accessory branches of the TMB[96]. The preva-

Fig. 17. *TMB (arrows) arising from the ulnar side of the MN (arrowheads)*

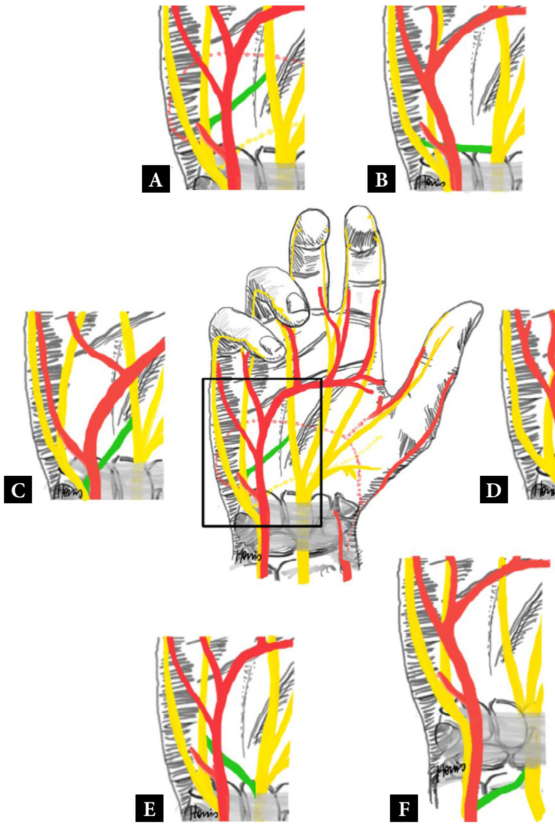

Fig. 18. *Anatomical variations of the PCB1 (Berrettini branch) (green): PCB1 originating from the UN, more than 4 mm distal from the FLR (***A***), perpendicular PCB1 close to the FLR (***B***), PCB1 originating from the UN, proximal to the FLR or less than 4 mm distal (***C***), more than one communicating branches of the PCB1 (***D***), PCB1 originating from the MN (***E***), PCB1 originating proximal to the bistyloid line (***F***)*

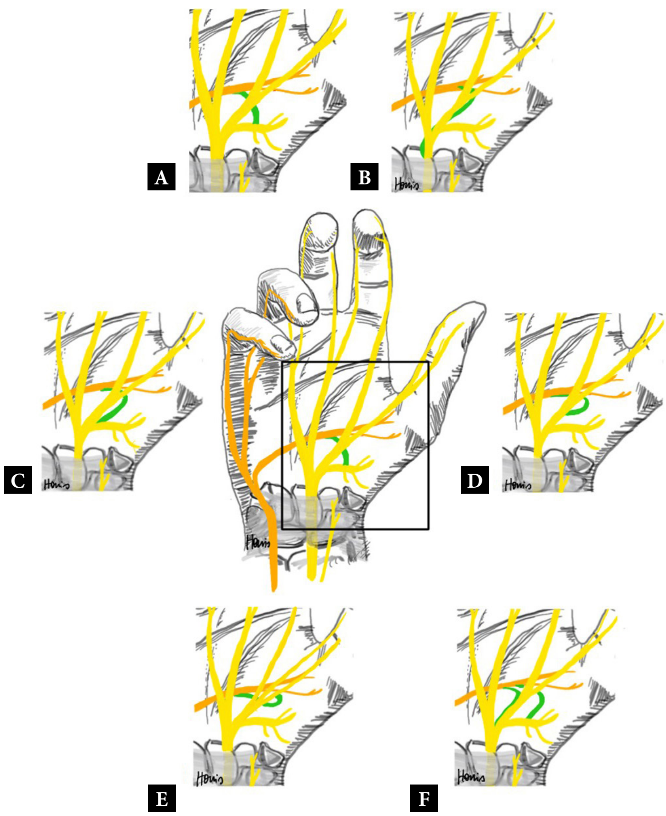

Fig. 19. *Anatomical variations of the PCB2 (Riché-Cannieu anastomosis) (green): normal PCB2 linked to the TMB (***A***), PCB2 linked to the MN trunk (***B***), PCB2 linked to the MN at the level of its divisions into the CPDNs (***C***), PCB2 linked to one of the CPDNs (***D***), PCB2 linked to one of the PPDNs (***E***), more than one communicating branches with different connection points (***F***).*

lence of bifid or even trifid MNs is described in chapter "Variability of anatomy of the carpal tunnel".

Lanz Type 4 (Fig. 16 J–M) includes accessory motor branches proximal to the CT that may escort the MN through the CT either with or without merging, perforate the FLR or even come from the ulnar side of the MN, which occurs in 2% of cases[55]. These types are rare but carry a risk of iatrogenic injury[97].

Whereas Hurwitz *et al*. stated that variations of the TMB are more often unilateral[92], other authors documented bilateral hand symmetry in the course of the TMB in 70%[55] – 100% of cases[93].

Knowing the varieties of the TMB is important to prevent iatrogenic damage, as this nerve is colloquially called the 'Million Dollar Nerve' due to high legal costs called upon surgeons/ hospitals for accidental damage of this nerve during operations[98].

Anastomoses between the median and ulnar nerves at the palm

Between the MN and the UN, there are four common anastomoses, known in clinical practice as Martin-Gruber anastomosis[99], Marinacci communication[100], Riché-Cannieu anastomosis[101,102], and Berrettini branch[103]. The first two lie within the forearm, while the latter two lie at the palmar surface of the hand, which is of interest for surgical interventions in the wrist.

At the hypothenar eminence, the fourth common digital nerve of the UN connects with the third common digital nerve of the MN (PCB1), known in the clinical setting as the Berrettini branch (Fig. 18). The prevalence of the PCB1 is reported as between 80%[52,104], 85%[105], 90%[103,106] and 100%[90,107,108]. At the thenar eminence, the deep branch of the UN connects with the TMB (PCB2) before it enters the thenar muscles, known clinically as the Riché-Cannieu anastomosis (Fig. 19). The muscular rami of the communicating branch of both nerves together usually send branches to one or two muscles, namely to the FPB and the adductor pollicis[63,109,110]. The prevalence of the PCB2 is reported as between 55%[111], 77%[112], 83%[113], and 100%[63]. Yang *et al*. observed the PCB2 significantly more frequently in the right hand[114].

Variability of the anastomosis between the median and ulnar nerves at the hypothenar region

Ferrari and Gilbert were the first to classify the PCB1 into four groups, depending mainly on the direction of the branch[103]. In about 90%[103,105,106] of cases, this anastomosis runs slightly oblique

Fig. 20. *Rare constellation showing the PPDN (pointed by the scissors) arising from the PCB1 (arrows)*

Fig. 21. *PCB1 (arrow) with a sling (arrowhead) around the superficial palmar arch*

Fig. 22. *Proximal PCB1 (arrows) running superficial to the FLR. If no caution is given, this branch can be hooked (arrowhead) and injured during a minimally invasive CTR procedure*

Fig. 23. *PCB1 running close to the FLR, hooked (arrow) with knife*

from the lateral branch of the UN to the medial branch of the MN, which is allocated to the Ferrari and Gilbert group one or three. Characteristically for the first group is that the distance between the origin of the communicating branch and the distal margin of the FLR is more than 4 mm[103,105]. In the third group, the origin of the communicating branch is either proximal to the distal margin of the FLR or less than 4 mm distally, the course is steep with an angle. In the second group, the course of the anastomosis is perpendicular, not visible if it comes from the UN or the MN, close to the distal margin of the FLR. The fourth group includes all atypical communications that are either directed from the MN to the UN or double-branched[103].

As there is no official classification yet, descriptions of the PCB1 vary[52,105,111]. Some authors emphasize the variant in which the PCB1 arises from the MN or the third CPDN connecting to the UN, fourth CPDN or eight PPDN more distally in 7–8% of cases[105,106,115]. The PCB1 may split into multiple twigs and connect accordingly[116]. In rare situations, a PPDN may arise from the PCB1 (Fig. 20). The superficial palmar arch can perforate the PCB1[117] (Fig. 21). The PCB1 may occur proximal to the bistyloid line[105].

If the origin of the PCB1 is close to the distal margin of the FLR or steep to the UN, it is prone to iatrogenic injury, which is the case in the Ferrari and Gilbert types 2–4 (Fig. 22 and Fig. 23). This situation is reported as rare in some publications, with a prevalence of less than 5%[105], but common in others, ranging between 48%[52] and 50%[103].

Variability of the anastomosis between the median and ulnar nerves at the thenar region

According to Riché[101] and Cannieu[118], the PCB2 first appears between the two heads of the adductor pollicis, and then crosses the tendon of the FPL. According to the observations by Harness *et al.*, in half of all cases, the PCB2 shows variations to the original description[112].

Variations of the PCB2 typically stand in regard to the branch coming from the MN, e.g., the deep branch of the UN connects with a separate branch of the MN in 30%[63], one of the CPDNs or PPDNs in 25% of cases[63,119]. Double or triple anastomoses in this region may occur. The extramuscular course of the PCB2 is most common, recorded twice to three times more often than the intramuscular course. Occasionally, an association of extra- and intramuscular PCB2 occurs[63].

Double innervation of the thenar muscles has been confirmed both electrophysiologically and clinically[63,110,112]. The PCB2 double innervates one head of one thenar muscle more often (72%) than both heads of one (17%) or heads of different muscles (12%)[63]. There are also case studies that describe complete or nearly complete UN innervation of the thenar muscles through the PCB2[120–122].

Discussion

Good knowledge of possible anatomical variations in this region is crucial for safety-optimization of different surgical procedures at the volar aspect of the wrist, e.g., US-guided carpal tunnel release, as injury might result in dysfunction, dysesthesia, and pain on wrist extension. Until now, for most variations, anatomical and surgical descriptions vary, as there are no official classifications yet.

The prerequisite of any CTR is the severing of the strangulating FLR as the mechanical focal point. However, the position at which the strangulating FLR is cut is – in the end – secondary, as the mechanical tension of the structure needs to be interrupted only to relieve the strangulated MN, which is a simple matter of mechanics. From an anatomical point of view, this transection should always be done ulnar to the nerve, as the typical branches of the MN carpal segment lie in the radial 'forbidden zone' for surgery.

Compared to open surgical procedures, HRUS-guided CTR offers the advantage that any anatomical structure of interest is visible at any time: before, during, and after the FLR is severed. This means that surgeons can avoid missing important anatomical structures and variations that are not visible without opening the tunnel, a maneuver called a 'double door' examination.

It is important for diagnostic sonographers and surgeons to consider all the anatomical variations discussed in this article to define specific pathologies and pain syndromes of the hand. In particular, the well-known branches of the median nerve (and their variants) that may cross the 'working space' in the carpal tunnel, also known as the 'Nakamichi space'[10], are of great significance for HRUS-guided CTR. However, variants of the branches that run radially to the carpal segment of the median nerve are less relevant, as this area is considered a 'forbidden zone' for any type of CTR.

A quite common branch running through the Nakamichi space is the PCB1 (Berrettini branch). This branch often intersects the space at an angle that is prone to inadvertent transection during HRUS-guided CTR procedures with a hook knife[18]. While any resulting sensory disturbance may not be particularly significant, a neuroma resulting from this type of anastomosis might cause tingling pain with each fist bump, which would be a more pressing problem.

Normally, more distal nerve branches, such as the ulnar CPDN, are not of immediate concern in CTR procedures, as they are further from the distal border of the FLR and, therefore, less at a risk of direct transection. Nevertheless, it is important to keep these branches under 'visual' control or ideally avoid any interference with them before the first incision is made.

In HRUS-guided CTR interventions, the palmar PMA is more important than the superficial palmar arch, which is only necessary to identify the most distal boundary of the 'intervention region'. The safe Nakamichi space is clearly defined by this arterial structure. While the palmar PMA can be important for the perfusion of the internal MN, they are sometimes located close to the ulnar aspect of the MN, which can be an obstacle in certain cases. In these situations, the course of the palmar PMA is more important than its mere existence, as structures that can be caught on a hook are always at a risk of being accidentally severed.

In summary, certain structural variations within the carpal tunnel are particularly prone to unintended damage both in traditional surgical CTR and newer HRUS-guided CTR procedures. It is, therefore, important that these variations are identified and accounted for to ensure the safety and therapeutic success of these procedures. If aware, these variations should be looked for, especially when using HRUS, and any unintended harm must be avoided in daily clinical practice.

Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations which might negatively affect the contents of this publication and/or claim authorship rights to this publication.

Author contributions

Original concept of study: HRH, HG, BM, AL. Writing of manuscript: HRH, HG, AL. Analysis and interpretation of data: HRH, HG, SH, MK, BM, AL. Final approval of manuscript: HG, SH, EB, ESO, AL. Collection, recording and/or compilation of data: SH. Critical review of manuscript: HG, MK, BM, EB, ESO, AL.

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