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ORIGINAL ARTICLE

Presentation of the vascular supply of the proximal ulna using a sequential plastination technique

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Abstract
Purpose The purpose of this study was to demonstrate the peri- and intraosseous vascular supply of the proximal ulna.
Methods Eleven fresh human cadaveric elbows were sequentially plastinated beginning with arterial injection, followed by block and secondary slice plastination of the whole elbow. With this technique, we obtained completely transparent cadaveric slices in which the peri- and intraosseous vascular architecture could be studied.
Results Proximal ulna vascularization is due to an arterial network: a superior and inferior collateral ulnar artery and the profunda brachial artery climbing to the olecranon from proximal. An anterior artery and a posterior recurrent artery climb up distally to the medial parts of the ulna and an interosseous recurrent artery is responsible for the lateral and posterolateral proximal part of the ulna. The intraosseous vascularization is due to directly penetrating branches out of the posterior recurrent ulnar artery and a vascular plexus at the olecranon tip. In addition, we saw a major distal bone penetration branch coming from the recurrent posterior artery, climbing intraosseously without junction to the proximal penetrating branches.
Conclusion The peri- and intraosseous vascularization of the proximal ulna was shown. A transitional zone of the intraosseous vascularization of the proximal ulna was detected.

Keywords Vascular supply of the proximal ulna · Plastination · Olecranon fracture · Elbow

Introduction

Fracture nonunion or nonunion of olecranon osteotomies for elbow fracture exposition is well known in addition to triceps insufficiency after total elbow arthroplasty [3, 14, 15, 17, 20]. It is important to understand the vascularization of this region in order to avoid nonunion or tendon healing problems, which might be due to perfusion problems. Besides the description in standard anatomical textbooks, there is limited information on the extra- and intraosseous blood supply of the adult proximal ulna. Only a few publications describe the extra [4–6, 12, 26, 27] and intraosseous [5, 26, 27] vascular anatomy of the proximal ulna yet. All of them used Latex injection techniques and chemical debridement for extraosseous vascularisation, and India ink injection followed by Spalteholz clearing for the intraosseous vessels. The aim of this study was to demonstrate the blood supply to the proximal ulna using a two-step, sequential slice plastination technique so that extra and intraosseous vascular anatomy could be studied in the same specimen.

Methods

Cadaveric studies were performed at the Department of Anatomy of the University of Cologne, Germany. Eleven fresh human upper extremities were used for this study. There were seven right and four left sides elbows from eight male and three female donors. The same specimens were used to study the intra- and extraosseous vascular

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anatomy of the radial head [11] and the arterial blood supply of the distal humerus [25]. Specimens were obtained from the cadavers aged from 71 to 85 years without any history of traumatic elbow injury. All specimens were prepared according to the sequential plastination technique [18, 19]: after separation of the limb from the cadaveric body, the complete upper extremities were perfused and cleaned with saline solution. As the next step, 4 % formalin solution was perfused through the arterial vessels for preliminary fixation of the specimen at 1–3 °C for 24 h. After that acetone wash out was performed up to 10 times to restore the natural color or the specimens. As the next step, red color containing lead (Pb) epoxy resin (Biodur ® E20 and Biodur ®hardener E2) was injected. To prevent a transfer of the lead-containing resin to the venous system, a special granularity of the lead was used (Grain size 99 % less than 0.00063 cm). Now the complete upper limbs were frozen and the distal forearms were separated from the elbow joints. X-rays of the specimens were taken to document successful injection before further preparation was performed. Dehydration was performed using acetone (99 %, ≤25 °C) for at least 4 months. Then tissue water was exchanged to a medium that is appropriate to be replaced by the epoxy resin, followed by a degreasing process with dichloromethane for several weeks. After dehydration and degreasing, we obtained specimens in which the intra- and extracellular liquid is completely acetone. Acetone and dichlormethan are known for having low boiling points which the epoxy resin does not. The elbows were now placed into chambers filled with epoxy resin for another 3 weeks. Due to the chemical properties of the used elements a continuous vacuum application replaces the acetone and dichlormethan by the resin. After the epoxy resin blocks had hardened, an anatomical saw was used to cut all specimens at a slice thickness of 4 mm. At this point of preparation, the slices were opaque. Further—or so-called—secondary plastination was then performed by placing these slices into a chamber 1 cm in diameter; then, the slices were poured out again with epoxy resin (Biodur ® E20 and Biodur ® E2 hardener). Finally, the hardened, secondarily plastinated slices were completely transparent and ready for anatomical study.

Results

Vascularization of the proximal ulna is due to several major and minor branches. Coming down the arm from proximal, the superior ulnar collateral artery is rising out of the brachial artery a mean of 7.3 cm (6.3–9.3 cm, $n = 11$) proximal to the medial epicondyle. An inferior ulnar collateral artery is coming out of the brachial artery 4.7 cm (3.1–6.5 cm $n = 11$) proximal to the medial epicondyle. Further proximal, the profundal brachial artery out of the main brachial artery that is also responsible for the vascularization of the proximal ulna is coming from proximal.

In the area between the descending vascularization coming from proximal, such as the superior and inferior collateral artery and the profundal brachial artery to the elbow joint, we could detect accessoric branches out of the brachial artery going directly to the ulnar bone in 2 of 11 specimens (Fig. 1).

The distal arising vascularization of the proximal ulna comes out of the ulnar artery. 4.1 cm (3.6–4.9 cm, $n = 11$) distal to the medial epicondyle, the brachial artery bifurcates into the ulnar and radial arteries. Vascularization ascending to the proximal ulna is due to several branches from the ulnar artery:

A main arterial branch was seen either as a common recurrent ulnar artery in 6 of 11 specimens, or as two separate branches, an anterior and posterior recurrent ulnar artery, in 5 of 11 specimens coming out of the ulnar artery directly a mean of 5.0 cm (4.0–5.6 cm, $n = 5$) distal to the medial epicondyle (Fig. 2).

6.7 cm (5.4–9 cm $n = 11$) distal to the medial epicondyle just close to the common recurrent ulnar artery, we saw the interosseous recurrent artery ascending to the elbow joint between the ulna and radius responsible for the lateral and posterolateral parts of the ulnar bone's perfusion. In 5 of 11 specimens, we saw a common origin of the interosseous recurrent artery together with the recurrent ulnar artery out of the ulnar artery, and in 5 specimens this leaving was separate. In one specimen we did not see an interosseous recurrent artery. On its way up, it branches off to the lateral and posterolateral side of proximal ulnar bone. The interosseous ulnar artery ends in the arterial plexus of the elbow (Fig. 3).

On the palmar side of the proximal forearm, the anterior recurrent ulnar artery is running through the flexor muscles to the palmar aspects of the proximal ulna and the coronoid process and further on to the radial parts of the proximal ulna. Here, we saw an anastomosis to the inferior collateral artery coming down from the brachial artery in 4 out of 11 specimens (Fig. 4). The posterior recurrent artery is ascending at the medial side of the proximal ulna to the elbow joint. Its branches reach the olecranon tip and the medial epicondyle (Fig. 5). In this area, we saw an anastomosis to the superior ulnar collateral artery in 7 of 11 specimens, and to descending branches of the profundal brachial artery in 5 of 11 specimens (Fig. 6). Furthermore, in one specimen we saw an atypical position of the posterior recurrent artery ascending more ventrally, responsible for the vascularization of the coronoid process.

In summary, in the cubital fossa and the dorsal area of the olecranon, we saw a well-perfused area with multiple small and very small anastomoses between the above-

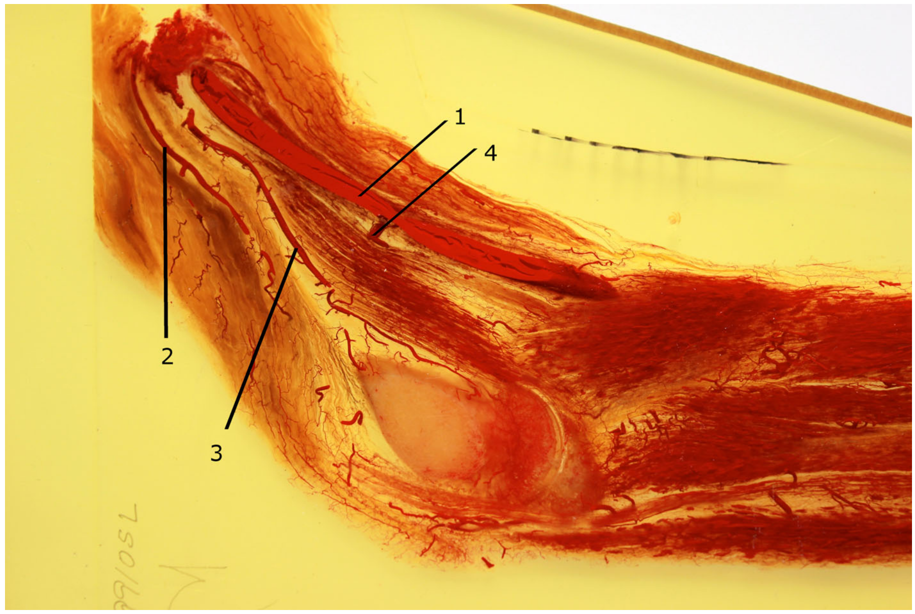

Fig. 1 The descending main vessels to the olecranon: *1* brachial artery; *2* profunda brachii artery; *3* superior ulnar collateral artery; *4* inferior ulnar collateral artery

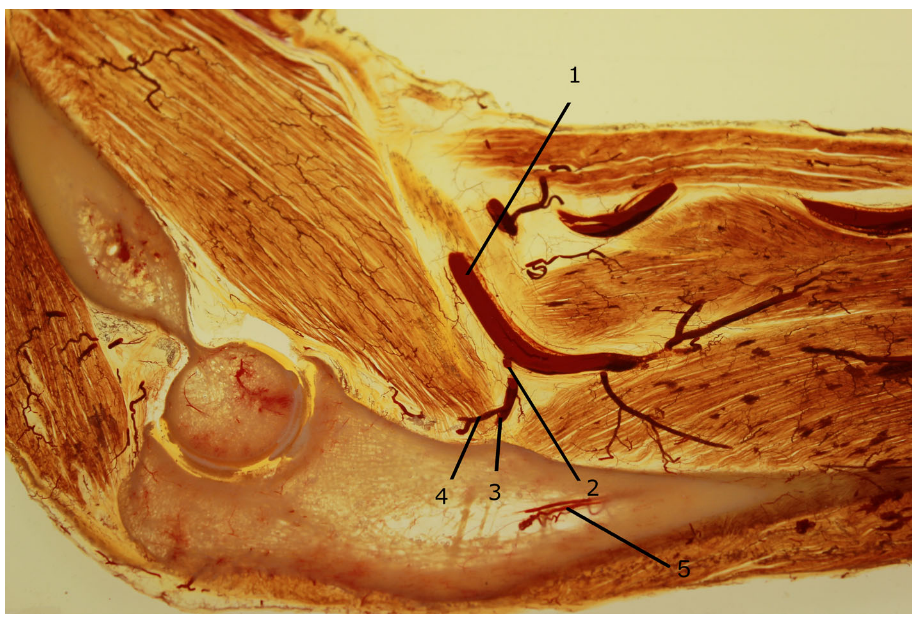

Fig. 2 The branches of the ulnar artery (*1*) the main arterial branch was seen as a common recurrent ulnar artery (*2*) and the anterior (*3*) and posterior (*4*) recurrent ulnar artery. Also the intraosseous branch can be seen (*5*)

mentioned vessels, creating a plexus situation for the microscopic extra- and intraosseous vascularization of the proximal ulna. In fact, we saw anastomoses between the anterior and posterior recurrent ulnar artery in 6 out of 11 specimens. In all specimens, we saw junctions between descending branches of the profunda brachial artery to the posterior recurrent ulnar artery coming from dorsal and to the superior and inferior ulnar collateral artery. Figure 7 shows a schematic picture of the periosteal vascularization of the proximal ulnar bone coming from proximal (Fig. 7a) and distal (Fig. 7b). It also shows the division of the blood supply directing into three compartments (medial, radial, and ventral; Fig. 7c).

The intraosseous perfusion of the proximal ulna shows a special situation

Besides the multiple bone-penetrating branches at the olecranon tip, we saw a major bone-penetrating branch 4.6 cm distal to the medial epicondyle in 4 out of 11 specimens. This branch has its origin in the common recurrent ulnar artery in one specimen and in the posterior

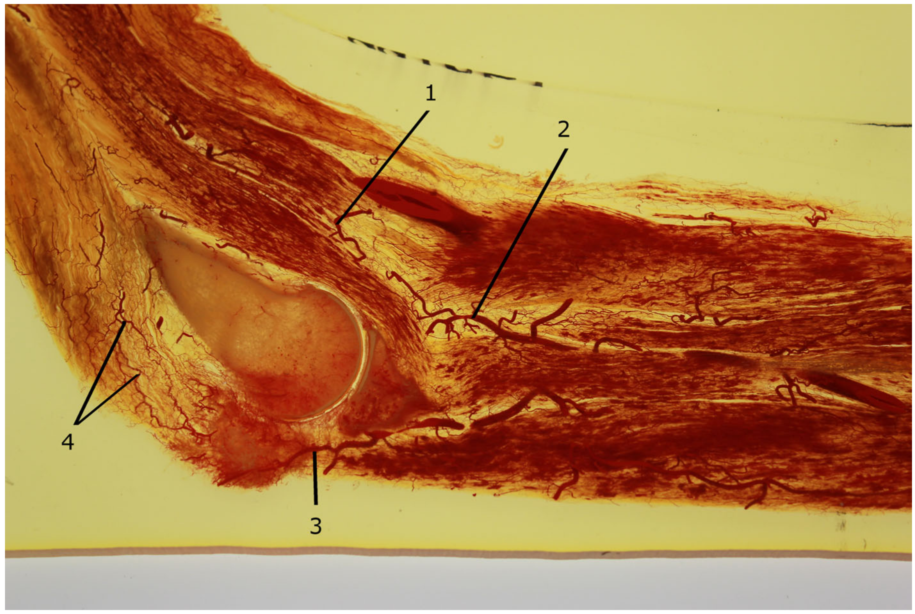

Fig. 3 Branches of the larger vessels creating the arterial plexus of the elbow: branch of the brachial artery (*1*), branch of the anterior recurrent artery (*2*), branch of the posterior recurrent artery (*3*), and branch of the profunda brachial artery (*4*)

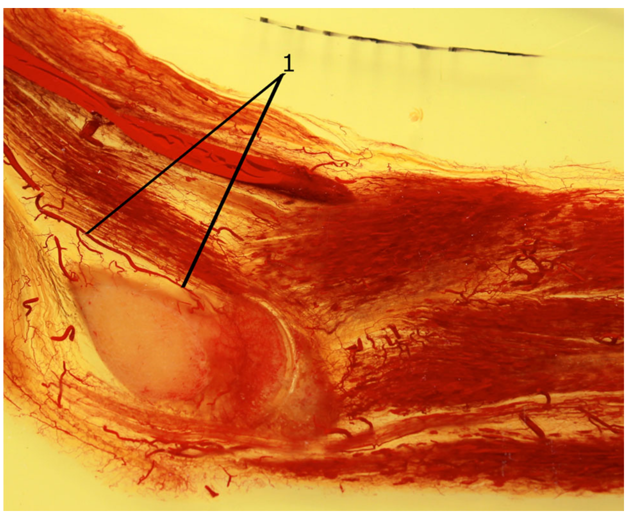

Fig. 4 The anastomosis between the inferior collateral ulnar artery and the anterior recurrent ulnar artery (*1*)

recurrent ulnar artery in three specimens (Fig. 8). It climbs proximal to the olecranon tip without a direct junction to the proximally penetrating vessels coming mainly out of the posterior recurrent artery.

Discussion

Early in the 17th century, Jan Swammerdamm was the first to perform studies of vascular anatomy with melted wax for scientific reasons [16]. The most important time of corrosion techniques in anatomy was in the middle of the 19th century in Vienna. Joseph Hyrtl used a mixture of mastic and wax, later natural resins, and gelatin colored with particular mineral substances for his studies. The first user of polymerized synthetic material (Plastoid) was Schummer in 1935 [24]. Vessel injection with polymerized synthetic material, followed by maceration of the whole organic material developed a three-dimensional imprint of the vascular architecture, but lacked soft tissue. Additionally, very small vessels might also have been destroyed and subsequently missed [13]. Spalteholz's technique can be performed to study intraosseous vascular architecture after decalcification of specimens' bony structures. In fact, with these two preparation techniques vascular anatomy can only be studied either extraosseous or without bony structures in different specimens. A secondary plastination technique, first described by Rath and Koebke [18, 19], enables the combination of peri- and intraosseous visualization of vascular structures in the same specimen. However, a shared problem of all injection techniques is the possibility of missing details of the vascular anatomy even in very fresh specimens due to the degeneration of the small vessels unable to be completely filled during the injection process.

Only a few authors describe elbow vascularization, with the vascularization of the proximal ulna being even more rare: Menck et al. [12] saw the ulnar artery with its periosteal branches responsible for the ventral aspect of the ulna. Medially, the recurrent ulnar artery coming from the ulnar artery splits into an anterior branch on top of the brachial muscle with a junction to the inferior collateral ulnar artery and a posterior branch dorsomedially running with the ulnar nerve at the medial aspect of the olecranon. The vessel forms a junction with the superior collateral

Fig. 5 Branches of the posterior recurrent ulnar artery (*1*) running to the olecranon tip and the medial epicondyle

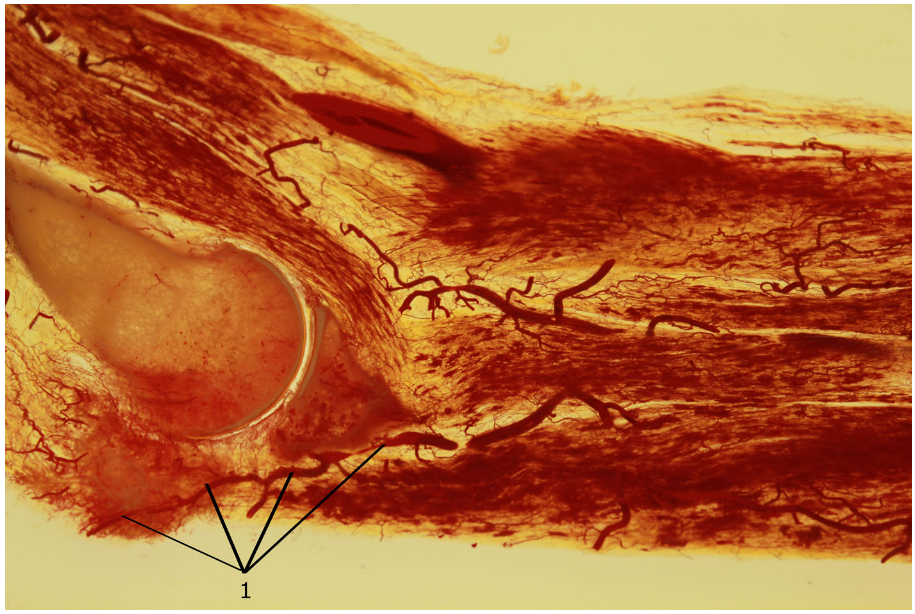

Fig. 6 The area of the medial epicondyle (*3*) with and anastomosis between the superior ulnar collateral artery (*1*) and the posterior recurrent ulnar artery (*2*)

ulnar artery. We were able to verify this arterial pathway in our study. As Menck et al. [12] and Yamaguchi et al. [26] reported, we saw the interosseous recurrent artery responsible for the dorsal parts of the olecranon.

Furthermore, we could confirm the results of Yamaguchi [27] with the posterior recurrent artery being responsible for the medial parts of the olecranon and a vascular plexus at the tip of the olecranon near to the triceps tendon insertion.

Regarding interosseous vascularization, Yamaguchi et al. [27] describe numerous intraosseous anastomoses in the region. In all specimens, they saw blood supply from the medial and lateral sides corresponding to several osseous perforators from the posterior ulnar recurrent and the interosseous recurrent artery. An intraosseous artery comes from the mid ulnar region proximally until to the level of the coronoid process just distal to the lesser semilunate notch. Hardy et al. [6] also saw this large intraosseous recurrent artery as a branch of the ulnar artery. It enters the anterior cortex of the ulna distal to the coronoid base. Besides several bone-penetrating vessels at the tip of the olecranon, we could confirm a large intraosseous ascending vessel out of the common or posterior recurrent ulnar artery in four specimens. As we did not see any junction between

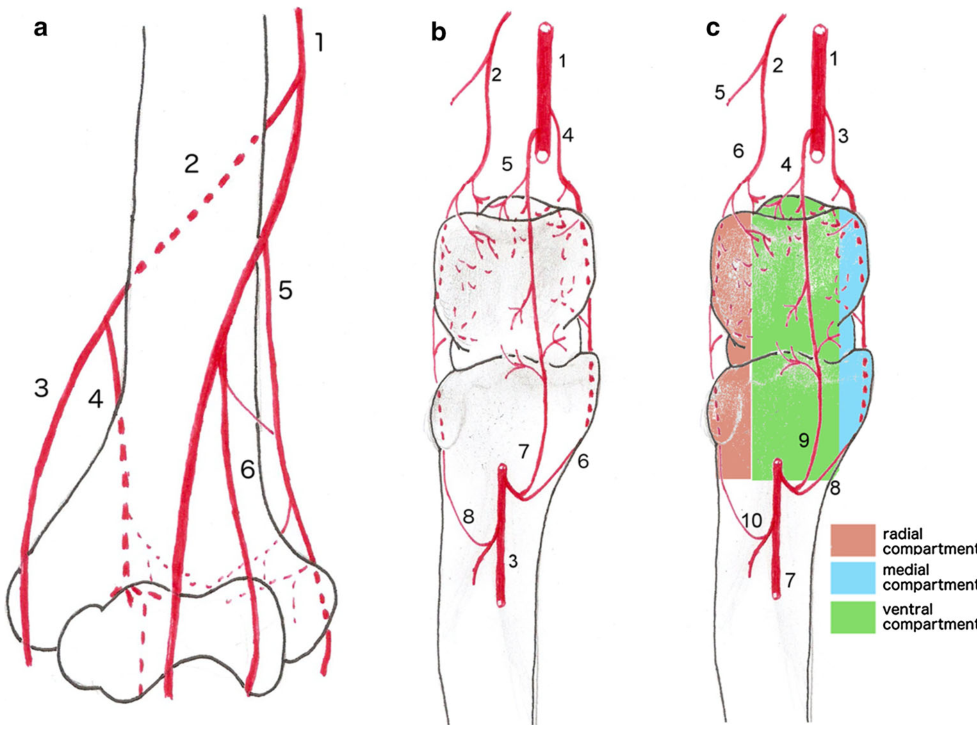

Fig. 7 A schematic presentation of the extraosseous vascularisation of the humeroulnar joint. **a** *1* A. brachialis; *2* A. profunda brachii; *3* A. collateralis radialis; *4* A. collateralis media; *5* A. collateralis ulnaris superior; *6* A. collateralis ulnaris inferior. **b** *1* A. brachialis; *2* A. collateralis media *3* A. ulnaris; *4* A. collateralis ulnaris superior; *5* A. collateralis ulnaris inferior; *6* A. recurrens ulnaris posterior; *7* A. recurrens ulnaris anterior; *8* A. interossea recurrens. **c** *1* A. brachialis; *2* A. profunda brachii; *3* A. collateralis ulnaris superior; *4* A. collateralis ulnaris; inferior; *5* A. collateralis radialis; *6* A. collateralis media; *7* A. ulnaris; *8* A. recurrens ulnaris posterior; *9* A. recurrens ulnaris anterior; *10* A. interossea recurrens

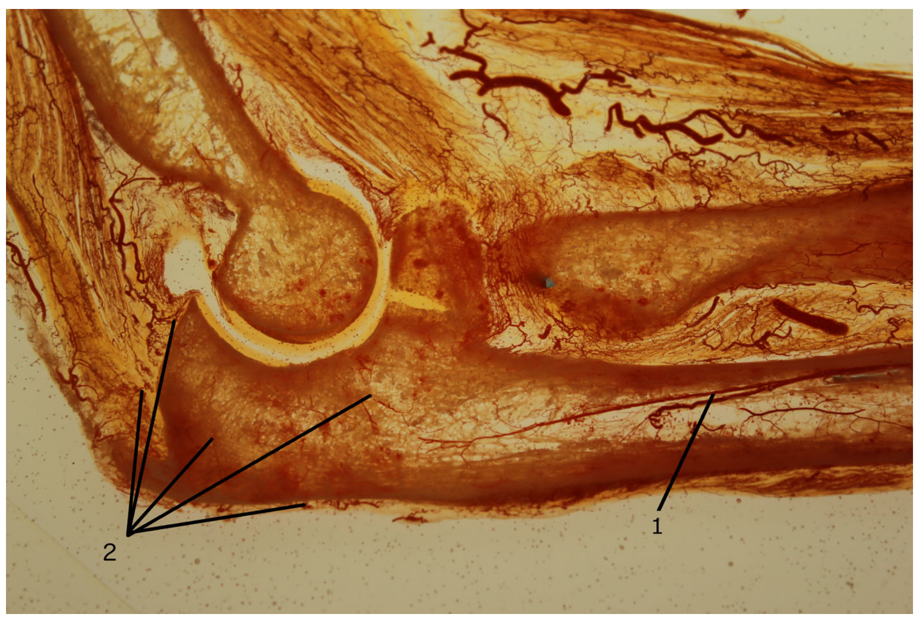

Fig. 8 A large intraosseous branch (*1*) ascending from the distal ulna to the olecranon, as well as nutritiant branches from the cubital plexus penetrating the bone from proximal (*2*)

this large intraosseous ascending artery and other bone-penetrating arteries at the tip of the olecranon, we could confirm the idea of a watershed between these two different regions of vascularization first described by Hardy [6].

Fracture fixation of the olecranon as a part of the proximal ulna is traditionally performed using the tension band technique, but a rising number of implant-related problems such as migration, delayed union, ulnar nerve palsy, secondary fracture displacement, soft tissue problems, local pain, and re-interventions were reported [7–10, 22, 23]. Taking this high complication rate into account, single dorsal or double plate fixation might become more popular, as it is recommended for more complex proximal ulna fractures [21]. Although the proximal ulna is well perfused, a large fracture exposition due to a proper plate position might result in a relevant implant-related bone devascularization with further implication for fracture healing. Furthermore, a nonunion rate of 30 % [1]

was reported after olecranon osteotomies for fixation of distal humeral fractures. The investigation of a watershed area in the middle of the olecranon may reveal vascular insufficiency during the bone healing of the olecranon osteotomy as a reason for these problems [6]. A recently published digastric olecranon osteotomy seems to be more preventive for the vascularisation of the proximal ulna and the extensor apparatus [2].

Before the use of the Mayo approach in elbow arthroplasty, triceps insufficiency as a complication of elbow arthroplasty had an incidence of 29 % [14] due to the devascularization of the triceps footprint with the interruption of small intraosseous perforators. Continuing the forearm and triceps fascia during the preparation decreases, but does not eliminate this problem. Knowledge of the vascularization of the proximal ulna enables preparation that preserves soft tissue with the aim of reducing complications in proximal ulna surgery.

In summery the arterial vascularisation of the proximal ulna was demonstrated with the sequential plastination technique. This basic knowledge of the arterial anatomy should be considered for proximal ulna surgery such as fracture and osteotomy healing and elbow arthroplasty approaches.

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