The management of traumatic nerve lesions in continuity is probably one of the most difficult challenges in peripheral nerve surgery, especially if there is clinical evidence of partial recovery and the neuroma involves the whole nerve section.

Nerve lesions of identical external appearance might harbor completely different internal pathological features: nerve fibers might be destroyed across the whole nerve section, leaving mainly fibrous tissue with interspersed mini axons. In such cases the nerve segment necessitates resection and grafting. In other cases the cross-section might contain enough prevailing conducting fascicular structures to enable spontaneous functional regeneration if only externally neurolysed. In a substantial number of cases the extent of nerve damage cannot be assessed with certainty by means of surgical exposure, external neurolysis, intraoperative nerve inspection, or palpation alone.

As Millesi et al.13 point out, these difficult lesions in continuity should be addressed with subtle and meticulous intraneural microscopic dissection. The underlying assumption is that although nerve fibers are not visible under the operating microscope, intact fascicles traversing the lesion will contain intact nerve fibers and therefore harbor the potential for spontaneous recovery.

In a different approach, Kline and colleagues7,16 emphasized the importance of intraoperative electrophysiological recordings (CNAPs) across the affected nerve segments. The absence of a CNAP 3 to 4 months after trauma indicates failure of adequate nerve regeneration and thus justifies resection and grafting of the involved...
nerve segment. In contrast, those cases still exhibiting complete functional loss, and yet depicting a recordable intraoperative CNAP across the lesion, will recover in up to 93% of cases without being grafted.

State of the art high-resolution ultrasound imaging of peripheral nerves is capable of displaying nerves with very high spatial (axial resolution up to 400 μm) and contrast resolution. Since the earliest reports of peripheral nerve ultrasonography, due to ongoing technical progress, ultrasound imaging can be considered as an established imaging modality in the preoperative evaluation of nerve compression, trauma, and tumors.

Intraoperative ultrasound in the management of nerve lesions

Concerning nerve trauma, preoperative ultrasound accurately identifies the site of nerve lesions with high sensitivity and specificity. Especially in the context of closed injury, ultrasonography may add valuable information about the site and extent of the underlying nerve lesion. It allows differentiation between traumatic lesions of the nerve itself and/or paraneural tissues (scar, callus). Furthermore, preoperative ultrasound can distinguish nerve transections from lesions in continuity in most cases.

However, there are significant restrictions attending preoperative ultrasonography of traumatic nerve lesions, as follows: 1) high-frequency ultrasound goes along with less tissue penetration (1.2 cm with 20 MHz) and therefore limits examination of deep-running nerves (for example, the sciatic nerve); and 2) trauma-related soft-tissue alterations such as paraneural edema, scar formation, or foreign bodies may hamper preoperative sonographic evaluation due to scattering or absorption phenomena. To overcome those restrictions and to enhance image quality further, intraoperative direct scanning of surgically exposed nerve segments seemed obvious. Intraoperative use of high-resolution ultrasound has the potential to depict intraneural architecture, to give valuable information about the type (intraneural/perineural) and amount of neural fibrosis, and hence might represent a major tool for the evaluation of the severity of traumatic nerve lesions in the near future.

This is the first study describing intraoperative ultrasound in traumatic peripheral nerve surgery. The aim of the present study is to evaluate the potential of intraoperative high-resolution ultrasound in the context of nerve trauma.

Methods

Study Protocol

Between July 2009 and January 2010, 18 patients (Table 1) with 19 traumatic or iatrogenic lesions of peripheral nerves of the upper and lower extremity were included in the study. The treatment protocol included surgical exposure of the damaged nerve segment, photo documentation, and intraoperative ultrasound and electrophysiological studies, including simple motor stimulation and CNAP recording. In case of resection of an affected nerve segment (9 segments), the results of neuropathological examination were correlated with the findings obtained using intraoperative ultrasonography.

Intraoperative Ultrasound

The nerve segment involved was dissected out as usual. Afterward the nerve was embedded in a special, sterile hydrogel (SonarAid, Geistlich Pharma), which served as an offset spacer and coupling medium in high-resolution ultrasound imaging of very superficial structures (for example, in dermatology; see Fig. 1). Intraoperative ultrasound examination (iU22, Philips Medical Systems) was performed using a steriley draped, small-footprint 15–7 MHz (Fig. 2) or alternatively a 17–5 MHz linear array ultrasound transducer.

Intraoperative Electrophysiological Studies

After surgical exposure of the damaged nerve segment, direct motor stimulation was performed proximal and distal to the lesion. Contractions of muscles innervated by the nerve were visually observed. Afterward CNAPs were recorded across the lesion as described elsewhere.

Results

Feasibility and Technical Aspects

Intraoperative ultrasound turned out to be time efficient; the mean time needed for preparation and scanning was 8 minutes. The examinations were best documented in film sequences, which were superior to single pictures due to the dynamic nature of ultrasound imaging.

Cross-sectional ultrasound was most important for the assessment of the intrinsic nerve structure as well as the paraneural tissues. For that it was very important to obtain true orthographic sections, which turned out to be demanding in case of curved nerve courses (for example, the peroneal nerve at the level of the fibular head) where the nerves are running out of the plane of the ultrasound probe. To assess the continuity of nerve segments, longitudinal sections proved to be helpful. Initial comparison of the 2 available high-frequency probes revealed differences in terms of handling and image quality. Handling of the small hockey-stick probe (15–7 MHz) was much easier, especially in deep-seated nerves and curved nerve courses. On the other hand, as expected, image sharpness and image resolution of the 17–5 MHz linear array transducer was superior, but unfortunately its intraoperative use was limited by handling problems caused by its size.

Evaluation of Ultrasound Images

Ultrasound images were grouped into 5 different categories, as follows. 1) Normal (Case 16): typical honeycomb pattern, no hyperechogenic areas epineurally, no caliber changes. 2) Epineural fibrosis (Case 12): typical honeycomb pattern, increased hyperechogenic tissue surrounding the nerve, no significant caliber changes. 3) Intraneural fibrosis (Case 2): marked increase of hyperechogenic tissue inside the nerve surrounding the hyperechogenic fascicles, no caliber changes. 4) Neuroma/partial neuroma (Case 4): increased nerve caliber, hyperechogenic internal structure, loss of honeycomb pattern or preserved honeycomb pattern at one edge of the le-
<table>
<thead>
<tr>
<th>Case No.</th>
<th>Nerve</th>
<th>Trauma</th>
<th>Time</th>
<th>Clinical Assessment</th>
<th>CNAP</th>
<th>Sonography Finding</th>
<th>Intraop Finding</th>
<th>Management</th>
<th>Histological Finding</th>
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<tr>
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<td>sharp</td>
<td>1 mo</td>
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* The CNAPs were elicitable across 2 preserved nerve fascicles.
sion as a sign of partial neuroma. 5) Transection (Case 5): detection of 2 nerve stumps without continuity in the longitudinal-section ultrasound.

Illustrative Cases

Case 16
This 17-year-old male patient presented 6 months after right supra- and diacondylar humerus fracture with complete ulnar nerve palsy that was directly related to the trauma and exhibited no signs of recovery. Neurological examination revealed marked ulnar nerve hypesthesia, hypothenar atrophy, and ulnar claw. Surgical exploration was scheduled.

On surgical exploration at the elbow level (Fig. 3), the ulnar nerve turned out to be in continuity, but was fixed due to scarring at the level of the sulcus. Intraoperative high-resolution ultrasound revealed a regular honeycomb-like fascicular pattern, no caliber changes, and only a little hyperechogenic tissue surrounding the nerve. Intraoperative electrophysiological studies demonstrated a CNAP of normal amplitude at low stimulation. External neurolysis and subcutaneous transposition was performed, and there was mild epineural scarring.

Case 12
This 36-year-old man presented 2 months after blunt strangulation trauma of his proximal forearm, with an incomplete ulnar nerve lesion that showed no signs of recovery. Neurological examination revealed marked ulnar nerve hypesthesia, moderate hypothenar atrophy, and a palsy score of 2–3/5 based on the Medical Research Council scoring system. There was yet no clawhand malformation. Surgical exploration was scheduled.

On surgical exploration at the proximal forearm (Fig. 4), as expected, the nerve was in continuity, but he did not present any caliber changes. There was some scarring, and the nerve appeared to be hardened. Intraoperative high-resolution ultrasound detected an increase of hyperechogenic tissue surrounding the nerve as a sign of epineural scar over a distance of 4 cm, a preserved fascicular pattern, and no significant caliber changes. A CNAP of diminished amplitude could be recorded at slightly elevated stimulation levels. Epifascicular epineurotomy revealed a thick and hard epineurium, which was partially resected (partial epifascicular epineurectomy).

Case 2
This 24-year-old woman presented with complete ulnar nerve palsy after elbow luxation and subcutaneous transposition of the ulnar nerve 11 months earlier (Fig. 5). Neurological examination revealed marked ulnar nerve hypesthesia/anesthesia, clawhand malformation, and atrophy of hypothenar and intrinsic hand muscles. Surgical revision was proposed after intensive counseling.

During surgical exploration at the elbow level, the formerly transposed nerve was dissected out. A stump neuroma of the medial antebrachial nerve of the forearm was detected. The ulnar nerve itself was in continuity, showing slight caliber changes. Intraoperative high-resolution ultrasound detected small caliber changes. Proximal to the elbow, hyperechogenic tissue surrounding the nerve was detected, which further distally merged into hyperechogenic tissue inside the nerve itself, surrounding partially preserved hypoechogenic fascicle-like areas. A CNAP of very small amplitude was preserved at maximum stimulation levels. Thus, resection of the damaged nerve segment with subsequent grafting was performed. Histopathological examination confirmed extensive intraneural scarring, with some preserved fascicular nerve structure.

Case 4
This 42-year-old man presented 8 months after complex chain saw trauma to his right forearm, with complete ulnar and median nerve lesion (Fig. 6). Neurological examination revealed amputation of the fourth finger at the level of the proximal interphalangeal joint, and marked atrophy of the thenar, hypothenar, and intrinsic hand muscles. There was some flexion contracture of the finger joints. There was complete ulnar and median nerve anesthesia.
Fig. 3. Case 16. Normal: radiograph (lower left) obtained after osteosynthesis of supra- and diacondylar humerus fracture. Intraoperative photograph (lower right) showing the ulnar nerve exposed at the level of the elbow (star denotes the medial epicondyle). Lines indicate the level of corresponding cross-sectional ultrasonographic images (upper left and right: star denotes the medial epicondyle). Intraoperative CNAP recording (upper center) obtained with low stimulation (2.5 mA).

Fig. 4. Case 12. Epineural fibrosis: intraoperative photograph (center) showing the ulnar nerve exposed at the level of the proximal forearm. Lines indicate the level of corresponding cross-sectional ultrasonographic images (upper). Intraoperative CNAP recording (lower) showing low amplitude at high stimulation (13.4 mA).
Surgical exploration revealed a thick neuroma in continuity with the median nerve, which was resected and grafted, and partial neuroma in continuity with the main trunk of the ulnar nerve, with the dorsal cutaneous branch of the ulnar nerve preserved at the ulnar aspect of the neuroma. After interfascicular dissection of the dorsal cutaneous branch out of the neuroma, the remainder of the lesion in the ulnar nerve main trunk had to be resected and grafted. Intraoperative high-resolution ultrasound of the median nerve showed marked caliber change, lost honeycomb-like fascicular pattern, and a marked increase in hyperechogenic tissue inside the nerve. The main trunk of the ulnar nerve exhibited the same ultrasonographic features, except the preserved hypoechogenic pattern in the ulnar aspect of the neuroma, corresponding to the intraoperative finding of preservation of the dorsal cutaneous branch of the nerve. No CNAP could be recorded from the main trunks of both nerves. Histopathological examination confirmed neuroma in the 2 specimens.

Case 5

This 17-year-old male patient presented with complete median nerve lesion 5 months after a cut with a piece of broken glass at the level of the distal right forearm (Fig. 7). Neurological examination revealed thenar atrophy and complete median nerve palsy, combined with severe hypesthesia.

On surgical exploration the median nerve appeared to be thickened and scarred, but in continuity. Interfascicular dissection revealed sharp nerve transection, with a short bridge of scar between the stumps. Intraoperative high-resolution ultrasound showed moderate thickening of the nerve in cross-sections, but because of the rather short defect between the nerve stumps in this case, longitudinal sections were especially helpful in detecting complete transection of the nerve. No intraoperative CNAP could be elicited. Neuropathological examination of the specimen confirmed neuroma in continuity with a very short bridge of fibrous tissue between the nerve stumps.

Summary of Illustrative Cases for the 5 Categories

Intraoperative ultrasound findings appeared to be normal in 5 cases, which went along with preserved CNAPs. Ultrasonographic epineural fibrosis was present in 4 patients. In those 4, intraoperative electrophysiological studies revealed preserved CNAPs, with low amplitude at elevated stimulation levels. Intraneural fibrosis was suspected in 1 patient with longstanding complete nerve lesion. Intraoperative electrophysiological studies revealed no CNAP at maximum stimulation. Neuroma (6 lesions) or rather partial neuroma (2) and the special category of nerve transection (1) were present in a total of 9 lesions, and this was confirmed by neuropathological examination.

Discussion

In the majority of closed traumatic nerve injuries, nerves are not actually transected. Instead, a lesion in continuity develops, which results in either a neurapractic, an axonotmetic, or a neurotmetic injury. Even in the most experienced hands, often it is still a difficult deci-
sion whether a neuromatous nerve segment needs to be left alone after simple decompression and external neurolysis, or if there is a need for intraneural dissection to detect partially fibrotic areas, which should be resected and grafted.

Oftentimes surgery for these lesions is inappropriately delayed because there are vague early clinical signs of recovery, which are frequently unreliable. For example, the progression of the Tinel sign along the path of the affected nerve can be misleading: at times it might be evoked because fine unmyelinated fibers pass the neuroma. However, those have but little predictive value with respect to motor recovery.

The depth of the underlying nerve lesion (neurapractic, axonotmetic, or neurotmetic) and its management cannot be determined by preoperative investigations, surgical nerve exposure, visual nerve inspection, or palpation alone. Therefore, Kline, with the technique of intraoperative CNAP recordings across damaged nerve segments, introduced a physiological approach to deal with those lesions in continuity: a recordable CNAP across a damaged nerve segment 3 to 4 months after injury demonstrates the presence of a sufficient number of myelinated fibers to indicate the regenerative potential of the underlying lesion.

On the other hand, Millesi and colleagues, with the detailed microscopic dissection of such lesions, stressed a morphological approach: intact fascicles traversing the nerve lesion are regarded as a rational surrogate for intact nerve fibers, assuming that intact fascicles will contain intact nerve fibers.

However, the technique of intraneural neurolysis is a controversial subject because of the potential risk of further damage to an already impaired nerve segment, which might have the potential for spontaneous recovery of variable extent if left alone.

High-resolution ultrasonography as a preoperative imaging tool in the evaluation of traumatic peripheral nerve lesions has proven to be very useful and is valued by increasing numbers of neurologists and nerve surgeons as an adjunct in decision making. Preoperatively, ultrasonography is already able to differentiate reliably between lesions in continuity and completely transected nerves. Thus, repair of nerves earlier recognized as being severed can be scheduled earlier, implying that patients will have improved chances at useful functional recovery.

However, the requirements for imaging of neuromas in continuity are far beyond the question of continuity. Imaging of those lesions should be capable of evaluating the internal structure of the neuroma. It should depict the type and amount of fibrosis and delineate isolated traversing fascicles. With its excellent spatial resolution, high-frequency ultrasound is unique and enables insight into the nerve’s ultrastructure. Nevertheless, preoperative percutaneous sonographic evaluation of nerve lesions in continuity has its limitations: first of all, tissue penetration of high sonographic frequencies is limited. Furthermore, trauma-related soft-tissue alterations such as paraneural edema, scar formation, or foreign bodies may hamper preoperative sonographic evaluation due to scattering or absorption phenomena. Additionally, by virtue of the curved anatomical course, strict cross-sectional or longitudinal imaging of nerves can be challenging.

To overcome those limitations, attempts at intraoperative application of high-frequency and high-resolution ultrasonography seemed to be the obvious choice. Direct scanning of surgically exposed nerve segments eliminates the inherent problem of minor tissue penetration, which goes along with high ultrasonographic frequencies. Consequently, intraneural structure can be depicted with high spatial and contrast resolution. Fascicles passing through a damaged nerve segment may be differentiated from neuromatous tissue more precisely.
Intraoperative ultrasound in the management of nerve lesions

This is the first study dealing with intraoperative high-resolution ultrasonography in surgery for traumatic nerve lesions. In a recent study by Lee et al., intraoperative high-resolution ultrasonography was confined to the detection of postoperative neuromas after mastectomy, facilitating focused excision and guiding the surgical approach. There are no studies dealing with intraoperative examination of nerve lesions in continuity by high-resolution ultrasound. The morphological information obtained by this intraoperative imaging technique allows for noninvasive assessment of the lesion extent. In our preliminary study, intraoperative ultrasound imaging proved to be very reliable, easy to handle, and correlated well with the electrophysiological investigations, microsurgical dissection, and histopathological findings. Even in partial nerve lesions, preserved fascicles passing the surgical dissection were depicted.

Conclusions

Intraoperative ultrasound is a promising, noninvasive method that seems capable of aiding assessment of the internal extent of a nerve lesion, and thus represents a major tool for noninvasive assessment of regenerative potential.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. There have been no grants or special material supplied to any of the authors contributing to this study.

Author contributions to the study and manuscript preparation include the following. Conception and design: Koenig. Acquisition of data: Koenig, Heinen, Pedro. Analysis and interpretation of data: Koenig, Schmidt. Drafting the article: Koenig, Pedro. Critically revising the article: Koenig, Schmidt, Kretschmer, Antoniadis, Koenig, Schmidt. Drafting the article: Koenig, Pedro. Critically revising the article: Koenig, Schmidt, Kretschmer, Antoniadis, Koenig, Schmidt.

References


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