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## High-resolution ultrasound of the supraclavicular brachial plexus—can it improve therapeutic decisions in patients with plexus trauma?

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**Abstract** Patients with major traumatic brachial plexus lesions benefit from early surgery, but they are seldom isolated by today's diagnostic workup. Subjects with ambiguous findings after such workups usually undergo a trial of conservative treatment and those without improvement delayed surgery. Our study focuses on this problem. Hence, the purpose of this study was to evaluate the impact of high-resolution ultrasound (HR-US) on patient recruitment for non-delayed surgery. Twelve patients after blunt shoulder trauma and standardized HR-US assessment who underwent plexus surgery were included in this prospective observational study.

Thereby, a total of 168 plexus elements were evaluated. All findings were compared to electrophysiological data if available and tested statistically against the gold-standard, i.e., surgical validation. Major plexus lesions were correctly detected by HR-US in nine patients (20 plexus elements). In two patients (five plexus elements), the lesion was underestimated by HR-US in relation to the gold standard (surgical inspection). Our analysis showed a high positive (1.0) and an acceptable negative predictive value (0.92) for the grading of traumatic plexus lesions with HR-US. Based on HR-US findings alone, 9 of 11 patients with objective major lesions would have undergone early surgery. In conclusion, HR-US proved a valuable tool for the triage of patients with traumatic lesions into surgical and non-surgical candidates.

**Keywords** Nerve ·  
Musculoskeletal · Ultrasound ·  
Brachial plexus

### Introduction

Traumatic brachial plexus lesions are infrequent—affecting about 1% of the multi-trauma patients, and approaching 5% in high-speed accidents—but result in debilitating consequences in a young-age patient group. Good functional recovery can only be achieved with the timely institution of treatment: early surgery is considered best for major lesions, but chosen under false premises, surgery may in

itself lead to a further compromise of the plexus. Therapeutic decisions concerning surgical or conservative therapy are therefore difficult to achieve. They are presently based on an assessment of the injury mechanism, clinical examination, neurological tests, electrophysiological data and results of imaging studies. Among the latter, MRI (magnetic resonance imaging) or CT (computed tomography) myelography are the only widely accepted modalities. However, according to the available literature, the sensi-

tivity and specificity of MRI and CT are low for extra spinal brachial plexus injuries. Reported positive predictive values are 71% in the plexus root level [1] and range from 50 to 90% in the plexus trunk and fascicle level [2–6]. Electrophysiological testing [7] aims at an appraisal of the degree of the neural damage and at a definition of the injury level in the acute or sub-acute setting. Quite often, however, it yields only ambiguous findings, and patients must undergo a trial of conservative treatment. If no signs of functional recovery are detected during repeated clinical and electrophysiological follow-up examinations over a period of about 5 to 6 months, surgical nerve inspection is advocated, because under these conditions some kind of major impairment (complete or incomplete interruptions) must be assumed [8, 9]. This present state-of-the-art concept confronts the surgeon with a dilemma: patients suffering from major lesions such as neural interruptions are known to recover better if operated on early [8–10], but a substantial percentage of these lesions is missed by the presently established diagnostic regime.

During the last years, a great deal of work has been published on the value of high-resolution ultrasound (HR-US) for the examination of healthy [11] and injured peripheral nerves [12–15]. Most clinical HR-US studies on the brachial plexus, however, solely focus on the value of sonography for the guidance of anesthesiologic procedures [16–20], while studies on the value of HR-US for the diagnosis of plexus pathologies are scarce [21–23]. As the plexus topography is evident [24–27] and also subtle neural pathologies are proven to be detectable by means of HR-US [28–31], assessments of suspected brachial plexus injuries by HR-US are consequential.

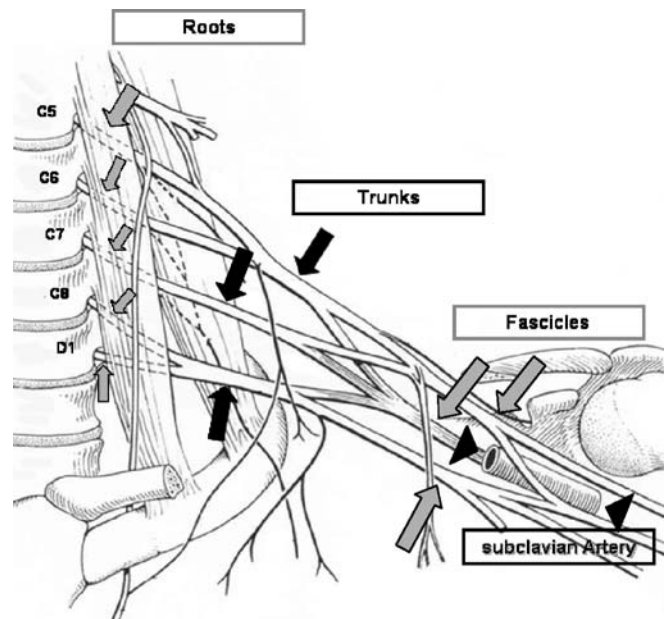
This prospective observational study aims to define the value of HR-US for the detection and grading of supraclavicular brachial plexus lesions and for the identification of surgical candidates.

## Subjects and methods

### Brachial plexus anatomy

The brachial plexus forms out of the ventral roots of the spinal segments C5 to D1. In the supraclavicular section, an inferior and a posterior trunk (primary cords) form to meet the three plexus fascicles (secondary cords) distal to the clavicle. The trunks and fascicles are named after their position and arrangement relative to the subclavian artery (Fig. 1) [24–27].

For our study purposes, the supraclavicular brachial plexus was divided into two levels: the root level and trunk level; the transition of the two levels was defined by the lateral border of the scalene muscles (exit of the interscalene gap). The plexus was further subdivided into four elements at the root level (roots C5 to C8) and into



**Fig. 1** Scheme of the brachial plexus. The plexus root elements are indicated and named at their exits out of the cervical spine (small grey arrows) by C6 to D1. The plexus trunk elements (superior, medial and inferior) are formed lateral to the interscalene gap (black arrows). The plexus fascicles (medial, lateral and posterior; large grey arrows) are named after their individual positions relative to the subclavian artery (arrowheads) distal to the clavicle

three at the trunk level (superior, inferior and posterior trunk) to ensure standardized HR-US assessment. The root D1 was excluded from patient assessment as—based on the cadaver investigation—it is only infrequently visualized with HR-US.

### Cadaver pilot study

One unembalmed fresh cadaver (male; aged 74 years) without a history of obvious shoulder trauma or surgery was used to investigate the sono-anatomic correlation of the supraclavicular brachial plexus. Informed consent for the use of the cadaver was given to the local institute of anatomy, which provided the specimen for this study.

Longitudinal (right side) and transverse (left side) HR-US plexus scans were recorded and the respective probe positions marked on the cadaver surface with a felt-tip pen (probe position) and pins (probe orientation). Subsequently, the cervico-thoracic regions were cryosected with a wire saw according to the marked positions and orientations (3-mm slices). The cryosections were marked, photographed and compared to the according HR-US images.

## Patients

Between September 2001 and April 2005, a total of 221 consecutive patients underwent standardized HR-US of the brachial plexus. Out of these, 12 male trauma patients (mean age 33.8 years, SD 14.5; range 16 to 62 years) with clinical evidence (including neurological examination and functional testing) of at least a minor plexus lesion who underwent plexus surgery (inclusion criterion) were included in this evaluation. All patients had given informed consent for the HR-US-procedure and, if a surgical

validation was obtained, a potential later inclusion of their data in a scientific evaluation. All procedures were performed according to the Helsinki Declaration [32]. Institutional approval by the local ethical board was granted (AN2347-231/4.9).

In all but two patients, EMG and ENG data were available. Data on the initial clinical presentation and the electrophysiological data of the patients are presented in Table 1. Two patients suffered from polytrauma including blunt shoulder trauma; one patient had undergone traumatic amputation of the upper arm after a severe traction

**Table 1** Clinical, HR-US and surgical findings in 12 patients with different traumatic plexus lesions

Patient, age, gender	Injury	Clinics-EMG/ENG	HR-US findings	Surgical findings
Pat. 1, 28, m	Chronic shoulder injury	Sensory and motor deficit C5/6, possible C7, <i>complete axonal damage C5/6</i>	C5 transition root/superior PI incl. NF, C6 swollen, C7 NPF	<i>PI C 5 incl. NF, beginning of scarring</i> AISNS, neurolysis
*Pat. 2, 41, m	Shoulder trauma by motorbike accident	Sensory and motor deficit C5–7, <i>complete axonal damage C5/6, partial C7</i>	Swollen hypo-echoic roots C5–7, scar formation	<i>CI C5/6 and PI C7; scars</i> AISNS, neurolysis
Pat. 3, 20, m	Complex sub-acute shoulder injury incl. fracture	Sensory and motor deficit C7/8, <i>complete axonal damage C7/8</i>	CI roots C 7/8	<i>CI C7/8</i> AISNS
*Pat. 4, 50, m	Polytrauma incl. shoulder trauma and clavicle fracture	Sensory and motor deficit all roots, <i>complete axonal damage C3-D1</i>	Swollen roots C5–8	<i>CI C5/6, swollen roots C7/8</i> AISNS
**Pat. 5, 62, m	Blunt thoracic and shoulder trauma	Sensory deficit with maximum C5/6 <i>not available</i>	Supraclavicular plexus swellings; fascicles with multiple scars	<i>Multiple scarring obstructing trunks of plexus,</i> neurolysis
Pat. 6, 16, m	Shoulder trauma from motorbike accident	Sensory and motor deficit C5/6 <i>not available</i>	<i>CI roots C5/6 with intact outer nerve sheath in C6</i>	<i>CI C5/6</i> AISNS
Pat. 7, 22, m	Blunt shoulder trauma	Sensory and motor deficit C5–7, <i>pain minor axonal damage not allocated</i>	<i>PI roots C5/6 with NF; C7 NPF; swollen fascicles</i>	<i>PI C5/6 incl. NF, beginning of scarring</i> AISNS, neurolysis
Pat. 8, 26, m	Polytrauma incl. shoulder trauma	Sensory and motor deficit C5/6, anterior cervical swelling, <i>diffuse plexus damage with upper accentuation</i>	<i>Hematoma in ASM with dislocation of root C5; CI C6 at osseous exit</i>	<i>CI C6, beginning of scarring</i> AISNS, neurolysis
Pat. 9, 50, m	Ski accident incl. blunt shoulder trauma and clavicle fracture	Sensory and motor deficit C5–8, <i>diffuse plexus damage with lower accentuation</i>	<i>C5–C7 swollen; hypo echoic root C6/7 with waist (PI) and NF</i>	<i>PI C6/7 incl. NF</i> AISNS, neurolysis
Pat. 10, 35, m	Shoulder trauma by car accident	Sensory and motor deficit whole plexus with inferior accentuation, <i>plexus damage C6/7 not classified</i>	<i>Swollen and CI roots C6/7 (C8 PI)</i>	<i>CI C6-D1</i> AISNS
Pat. 11, 20, m	Complex blunt sub-acute shoulder trauma after ski accident	Sensory and motor deficit whole plexus with superior accentuation, <i>plexus damage C4–6 not classified</i>	<i>CI C4–6 and PI C7 at transition to the trunk (3 cm lateral to exit)</i>	<i>PI C7 (3 cm lateral to osseous exit), CI C4–6, beginning of scarring</i> AISNS, neurolysis
Pat. 12, 35, m	Shoulder trauma by motorbike accident	Sensory and motor deficit C5/6, <i>diffuse plexus damage with upper accentuation</i>	<i>CI C6 at osseous exit with intact outer nerve sheath; PI C5/6 with NF</i>	<i>CI C6 PI C5/6 incl. NF</i> AISNS

EMG=electromyography; ENG=electroneurography; NPF=no pathologic findings; PI=partial interruption; CI=complete interruption; NF=neuroma formation; AISNS=autologous interposition of sural nerve segments; ASM=anterior scalene muscle

\*Patients with false-negative HR-US findings; \*\*patient with correct negative HR-US findings

injury in a motorcycle accident. Nine patients suffered from isolated blunt trauma to the shoulder region with (n=2) and without fractures (n=7).

Fourteen root and trunk elements (seven per side) were assessed in each subject; thus, a total of 168 supraclavicular brachial plexus elements were included in this study with available surgical correlation. The mean time elapsed between the accident and the HR-US evaluation was 5.5 months (SD 9.1; range 0 to 27 months), and 3.3 months between HR-US assessment and surgery (SD 4.6; range 0 to 17 months).

#### Study protocol (prospective observational study)

All patients received a standardized HR-US-investigation performed in a prospective fashion during daily clinical routine. By definition major neural lesions showed at least an incomplete or a complete neural interruption, and minor lesions were defined as irregular states of neural elements without interruptions. The standardized and detailed reports on the HR-US findings of those patients who underwent surgery (inclusion criterion) were selected, but without reassessment of the HR-US images. If available, initial EMG (electromyography) and ENG (electroneurography) data were compared to the HR-US findings. All surgical findings were photographed. Each therapeutic decision, if surgery was indicated or not, was made by the surgeon in charge based on all available findings, and in this context all medical decision-makers worked independently.

Comparisons of the HR-US data with the results of other radiological investigations such as MRI or CT, which were not performed routinely in the selected patients, were not the subject of this study.

#### Ultrasound examination technique and diagnostic protocol

All HR-US studies (cadaver and patients) were performed by at least two of three experienced radiologists in a standardized fashion on a HDI 5000 or iU22 (ATL-Philips, Wash., USA) using 5–12 MHz and 9–17 MHz broadband linear-array transducers. All sonograms were acquired with the application of image-compounding software (SonoCT). In some cases extended field-of-view scans were done for better illustration of obvious findings. The examiners were informed about the side of injury, but blinded to any other diagnostic result (clinical findings, electrophysiological test results, etc.). All scans were annotated regarding patient demographics, plexus levels and elements and stored electronically in the local PACS. All investigations were performed with the patient positioned supine, the head turned slightly (20–30°) away from the investigated side and the arms adducted.

All plexus elements as defined above with their typical HR-US appearance of peripheral nerve structures [24, 25] were scanned longitudinally and transversally along their individual course.

HR-US assessments were finished at the level of the clavicle, i.e., the distal border of the lateral cervical triangle. Each plexus element was compared to the corresponding non-injured opposite structure.

The segmental allocation of the root elements was done based on known structural vertebral characteristics such as the transverse processes of the sixth and seventh cervical vertebrae [17] in consensus with the vertebral artery entry into the foramen of the sixth transverse vertebral process [26]. The trunk elements were allocated according to their relative positions.

Each plexus element was primarily assessed for clear signs of major injury, and subdivided in complete lesions, defined by at least one clearly depicted neural stump and an according neural gap, and partial lesions, indicated by a focal neural caliber waist. The formation of neuroma, as an indicator for major neural lesions, was diagnosed if an ovoid, hypo-echoic tumor-like lesion was detected along the course or at the end of an impaired plexus element [27, 29].

Any other plexus changes, such as uniform or diffuse neural swellings with preserved continuity, were summarized as minor lesions [7, 15].

HR-US assessments of the surrounding soft tissues were performed additionally to search for hematomas, localized effusions and scarring [27–29]. The presence of such perineural pathologies was recorded, but did not influence the grading of neural lesions.

#### Statistical analysis

The surgical findings defined the gold standard against which all other diagnostic results were judged. All findings were tested concerning sensitivity, specificity, positive (PPV) and negative predictive values (NPV) and efficiency versus the surgical validation (major vs. minor lesion), and the Youden index (summarized test accuracy) was calculated. Due to the small sample number, no other statistically meaningful evaluations were performed.

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## Results

### US appearance

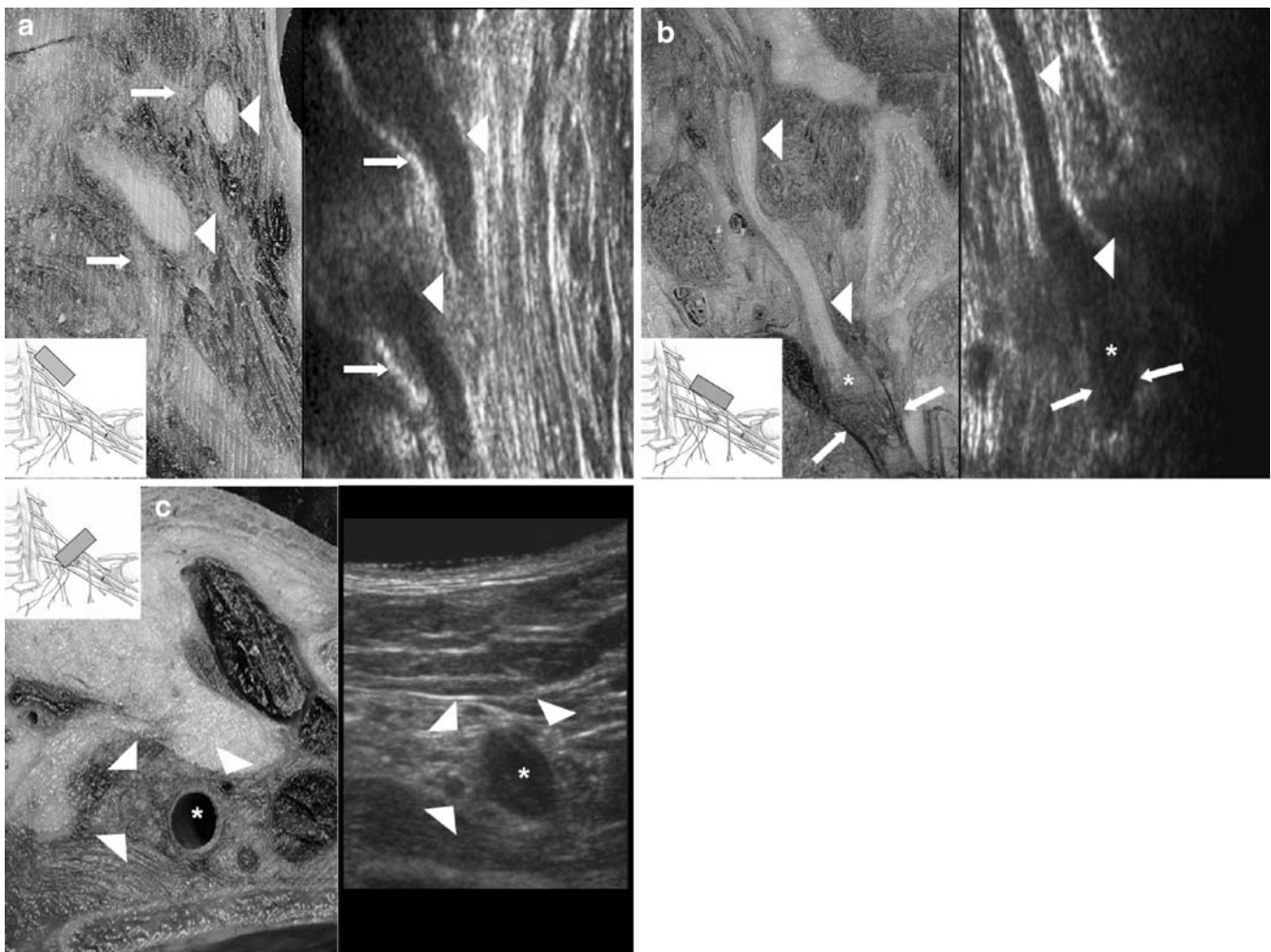
On comparison of cadaveric cryosections and the according HR-US scans, all intended plexus elements including the root elements C5 to C8 were visualized, clearly including a topographically correct allocation (Fig. 2a–c). All neural structures of the brachial plexus followed the known plexus topography and the basic HR-US pattern of

peripheral nerves [24–26, 28–30]. However, there were differences in the sonographic visibility, which was best, with the clearest bordering of the neural structures, for more superficial plexus elements as opposed to deeper main root and trunk elements. The root elements D1 were excluded from subsequent diagnostic assessment, as a reliable depiction was not achieved in this pilot investigation.

## US findings in patients

All intended elements of the injured and non-injured supraclavicular plexus were sufficiently accessible and visualized in all patients. Concerning the frequency-based resolution power of the two different applicators used, there were no apparent differences in the depiction of our morphological criteria for nerve injury.

HR-US diagnosed major lesions in 20 plexus elements of 9 patients. All were found at the root level with only secondary involvement of the according trunk elements, e.g., different degrees of local swelling. During HR-US



**Fig. 2** **a** Comparison of a coronal cadaver cryosection and the corresponding HR-US image (top=superior; left=medial): the neuroforaminal exits of the root elements C5 and C6 (arrows) and osseous borders (transverse processes) of the neuroforaminae are indicated (arrowheads). (Scheme of the according HR-US-probe orientation is shown in the bottom left corner). **b** Comparison of a pseudo-axial cadaver cryosection and the corresponding HR-US image (axial probe orientation angulated about 20 degrees vs. coronal plane; top=lateral; left=ventroinferior): course of the plexus root element C7 (arrowheads) out of the intervertebral foramen (arrows). Spinal ganglion of the root is indicated by an asterisk (\*).

(Scheme of the according HR-US-probe orientation is shown in the bottom left corner). **c** Comparison of a pseudo-sagittal cadaver cryosection and the corresponding HR-US image (sagittal probe orientation angulated about 10 degrees vs. transversal plane; top=superior; left=posterior): very lateral arrangement of the plexus trunk elements on the transition to the plexus fascicles (arrowheads) around the subclavian artery (\*). The right arrowhead indicates the superior, the left, the posterior and the bottom of the inferior fascicle. (Scheme of the according HR-US-probe orientation is shown in the top left corner)

examination, 11 of 20 major lesions were defined as complete and nine incomplete. In four of these patients neuromas were detected. In one patient a plexus-displacing intramuscular (anterior scalene muscle) hematoma was found in addition to a complete neural interruption (see Table 1).

HR-US diagnosed minor lesions at most in 64 plexus elements in affected sides in the 12 included patients. One patient showed only minor lesions due to obstructive perineural scarring, and nine patients various combinations of major and minor lesions (Fig. 3).

### Surgical correlation

In correlation with the surgical findings, electrophysiological data (EMG/ENG) proved inefficient regarding the exact topographic localization of lesions and differentiation between minor and major lesions (see Table 1). Major lesions (incomplete/complete interruptions) were present at surgery in 11 patients (92%). Of these patients, nine were correctly defined as surgical candidates with HR-US (Fig. 4)=detection of at least one major lesion as an inclusion criterion for surgery. Major lesions were defined minor with HR-US in two patients: During surgical inspection one of these showed complete interruptions of the segments C5 and C6, the other incomplete interruptions of the roots C5 to C7=five false negative elements (see Table 2). Surgical correlation for the definition of complete (Fig. 4) or incomplete (Fig. 5) interruptions with HR-US in major lesions was excellent, as only one root element

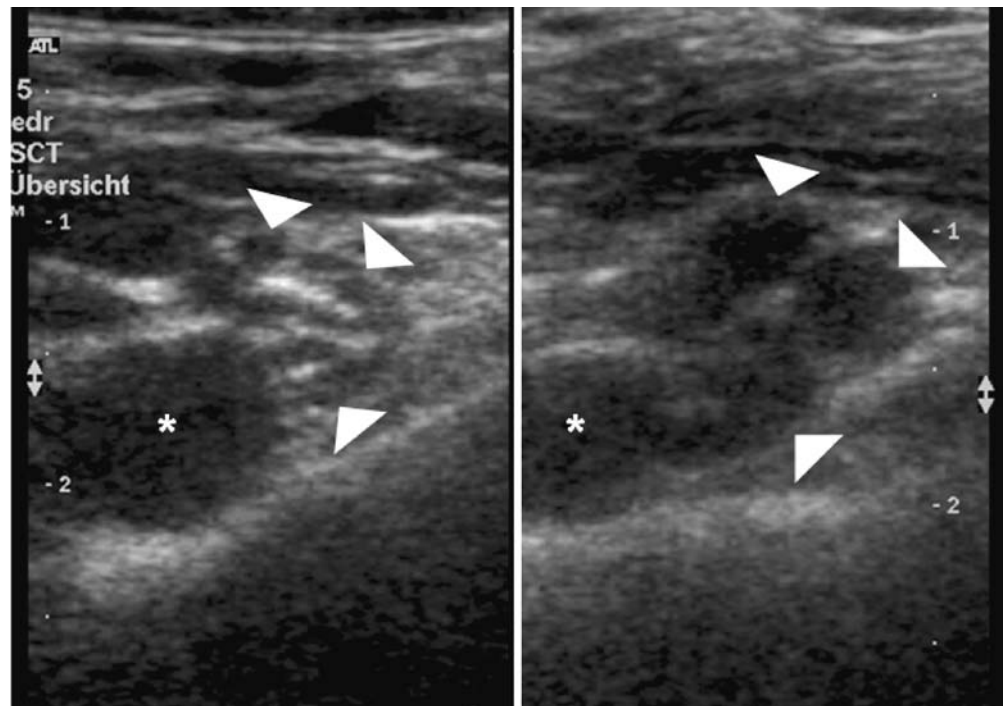
assessed incomplete was found completely ruptured during surgery (see Table 1). All neuromas detected with HR-US were approved by the surgeon, as was the allocation of major neural plexus lesions to the root level with only secondary involvement of the according trunk elements. Mere neural swelling with scar formation was confirmed by surgery in one patient rated minor with HR-US.

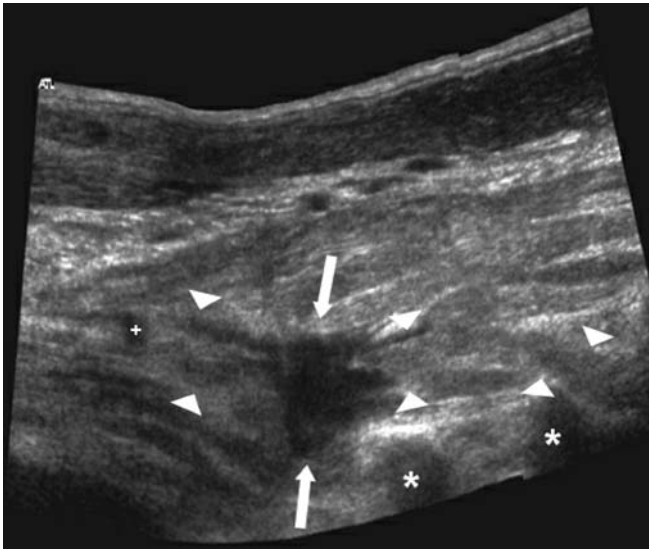
Statistical correlation between EMG/ENG and surgery was not performed. Statistical testing concerning the differentiation of major vs. minor lesions based on HR-US assessments in comparison to surgical findings resulted in a sensitivity of 0.8 and a specificity of 1.0 with a positive predictive value (PPV) of 1.0 and a negative predictive value (NPV) of 0.92. A high efficiency of 94% of HR-US with a Youden index (summarized test accuracy) of 0.8 was stated (see Table 2).

### Discussion

In addition to previous studies [16, 21, 23, 24], we can confirm that injuries of the supraclavicular brachial plexus are sufficiently assessable by means of HR-US. Graif et al. [24] already presented data on scarring and complete plexus ruptures in an overview on the HR-US of plexopathies, as did Mallouhi et al. in their case illustration [23]. Data on more frequently found partial plexus ruptures are presented in our paper for the first time. The main focus of this present study, however, was not to confirm results of previous investigations, but was laid on the differentiation of major and minor plexus lesions (which require a

**Fig. 3** Transversal scans of trunk elements (pseudosagittal probe orientation) of the brachial plexus in patient 2 after a motorbike accident. Opposite healthy side (left image), injured plexus (right image): Note markedly swollen trunk elements (arrowheads) with lost internal texture. The subclavian artery is indicated (\*). (Top=superior; left=ventral)





**Fig. 4** Longitudinal extended field-of-view scan of patient 11 after blunt shoulder trauma (ski accident) showing a completely ruptured root element C6 (arrowheads right to the interruption) with a gap, localized bleeding (white arrows) and slightly retracted neural elements. The hypo-echoic stripe (cross) depicted in the superior plexus trunk element was seen only in this extended field scan (neither swelling nor loss of neural continuity in standard scanning) and assessed as a motion-dependent artifact. Important landmarks for orientation, i.e., the transverse processes of the sixth (right\*) and seventh (left\*) cervical vertebra are shown. (Top=superolateral; left=inferolateral)

different therapeutic regime) [10] and to define sensitivity and specificity values for this differentiation. We clearly identified 9 of 11 patients (20 of 84 potentially suspect segments) with surgically proven major lesions (presenting at least partial interruptions), who retrospectively would have benefited from early surgery (PPV 1.0). In two subjects surgically defined major lesions (one patient with complete and one with incomplete interruption) were not detected by HR-US (overall five root elements; NPV 0.92). On retrospective review of the sonograms in the patient with the incomplete major lesion, the affected roots C5 to C8 showed a subtle, but somewhat uniform irregularity of the outer lining and internal structure, which was considered normal during the initial assessment. In the other patient who had a complete interruption of the roots

C5 and C6 very close to the foramen, an intense edema of the whole lateral neck impaired sufficient visualization of the paravertebral region.

Despite favorable technical aspects of HR-US, there are inherent limitations such as shown in the above examples. There certainly is a problem with lesions inside (neuroforamen) or below (clavicle) a bony structure, which is definitely beyond the scope of ultrasound and more apt to MR exams. We also found that the root elements D1, due to their topographic position, cannot be constantly visualized with HR-US, which is mainly a problem in short-necked patients. Thus, if a D1 lesion is suspected, further diagnostic work-up with MRI is strongly advisable. HR-US imaging may also be hampered in the acute posttraumatic patient, because of artifacts caused by interstitial bleeding and edema. Traumatized tissue has a reduced US transmission in general, which is due to an augmented water content. Therefore, small, but necessary details that for example help to differentiate neural edema from low-degree partial rupture might sometimes get lost or be overlooked.

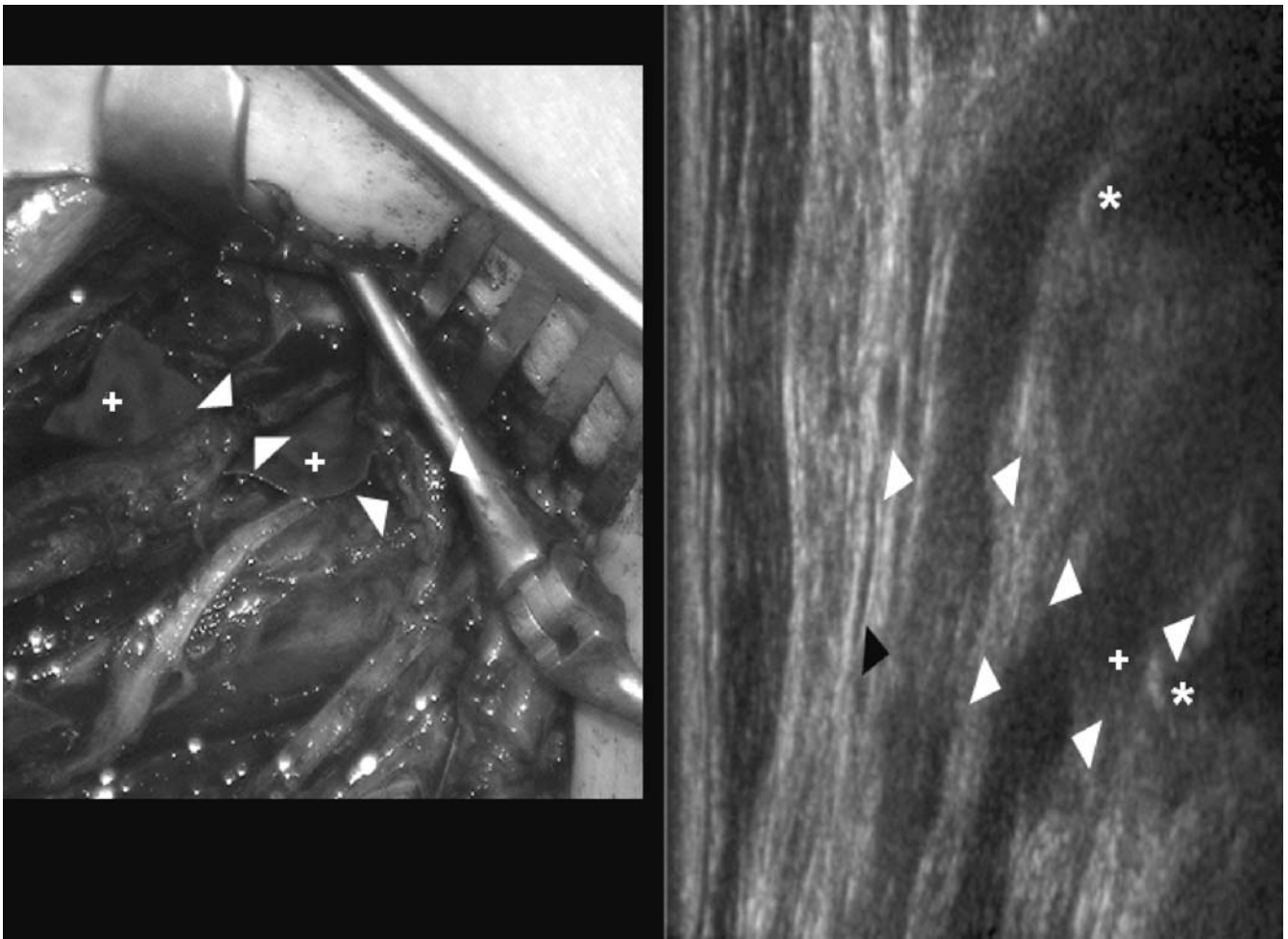
Despite these limitations, a rather high sensitivity (0.8) and a very high specificity (1.0) with a high Youden index (0.8) indicate an impressive accuracy and efficiency concerning the identification of major plexus injuries by the resolution power of HR-US for an assessment of such lesions. If the decision for or against surgery of the patients of this study had been based on our HR-US findings alone, all but two subjects with major lesions could have directly undergone immediate surgery [7, 8, 10].

The standardization of the assessment procedure with clearly defined HR-US criteria in terms of lesion type and clear topographic localization proved to be one key for reliable assessment. Especially with minor plexus lesions (e.g., diagnosis of a neural swelling), the comparison of conspicuous plexus elements with the corresponding structures of the opposite side proved helpful.

Besides being helpful for the categorization into major and minor lesions, HR-US may further be valuable with regard to the surgical approach to a lesion. Any additional information on the position and extent of a gap between plexus stumps and on the situation of the surrounding soft tissues (scarring, etc.) provided by HR-US should be beneficial for surgical planning. Such information allows

**Table 2** Comparison and statistical analysis of the HR-US assessments and surgical validations on impaired sides of the patients (n=84)

Analysis of plexus elements	Surgical major lesions	Surgical minor lesions
HR-US major lesions	20	0
HR-US minor lesions	5	59
Statistical analysis		
	Sensitivity (%)	80 (20/25)
	Specificity (%)	100 (59/59)
	Positive predictive value (PPV; %)	100 (20/20)
	Negative predictive value (NPV; %)	92 (59/64)
	Efficiency (%)	94 (79/84)
	Youden index (-1 to +1)	0.8



**Fig. 5** Comparison of the surgical situs (left image) and the corresponding HR-US findings (right image; coronar orientation; transverse processes indicated by \* in the right image) in patient 12 after a motorcycle accident. The intraoperative photograph shows the roots C5 and C6 (white arrowheads) marked by a little rubber tile (+ in the left image). Compare the hypo-echoic root element C5 with a waist (superior white arrowheads; right image) and a small irregularity further distally (black arrowhead), which represents an artifact in this extended field scan. The incipient neuroma formation

is not shown here. The root element C6 presents as completely interrupted with a very small gap (inferior pairs of white arrowheads, right image; + indicated the proximal stump) sparing the badly bordering outer nerve sheath (as confirmed by surgery). During surgery a partial interruption of the root C5 (left pair of white arrowheads in the left image) and a proximal complete and a distal partial interruption of the root C6 (not shown) were confirmed. (Left image: top=superior, left=posterolateral; right image: top=superior, left=lateral)

for a tailored and a possibly more gentle surgical approach. If and to which degree a patient's prognosis or postoperative outcome can thereby be altered should be evaluated by further studies.

Given a profound knowledge of the regional anatomy of the neck, and sufficient experience with examinations of the brachial plexus, HR-US is currently the modality with the best resolution. However, there are minimum requirements for plexus assessment, including high-resolution transducers of at least 12 to 15 MHz; image-processing tools such as X-REST™ or image compounding software (SONO-CT™) can reduce artifacts and therefore yield higher image quality and better results; extended field-of-view scans may prove valuable merely for the illustration of findings. However, they do not seem to be

mandatory and may sometimes be confusing due to artifacts (Fig. 4).

In our selected patient group, electrophysiological testing was only used for the validation of clinical findings. There are obvious and well-known limitations to electrophysiology concerning the definition of the exact location and extent of plexus damage. In none of the cases did EMG or ENG findings serve as sufficient indicators for or against plexus surgery. In this context, a thorough neurological examination is a better and more essential prerequisite in any plexus-injury patient. Any inconsistency of clinical and HR-US findings should result in clinical and HR-US short-term follow-ups. In our opinion, additional MRI investigations are expedient exactly here, tailored towards the detection/exclusion of neural damage in regions that are



not accessible with HR-US (intraspinal and infraclavicular). Only if neither clinical nor electrophysiological signs of improvement are found over time despite negative HR-US and MRI findings is investigative surgery of the supraclavicular plexus indicated. In this regard, neuroma formation needs some additional consideration: usually this is a rather easily made diagnosis in a peripheral nerve (a local nodular thickening in the course of a neural structure), and if detected in a patient with insufficient recovery after trauma during follow-up, a sign for a major plexus lesion, as a neuroma is always caused by axonal transection.

What is the position of HR-US in relation to other imaging modalities? We did not compare HR-US and MRI, so we cannot comment on such sensitivities or specificities. Future studies will certainly have to focus on this.

Based on our experience, we propose that HR-US should be the first line modality in the initial diagnostic workup of plexus trauma (after accurate clinical assessment), as it results in an early categorization of a suspected extra spinal plexus pathology and thereby helps to define surgical candidates in most cases. This should suffice in a majority of patients as indicated by this study. MRI investigations of the cervical spine surely must follow, at least if lesions of the intraspinal roots must be excluded. If HR-US is negative or only minor lesions are detected despite stringent clinical evidence for a major lesion, MRI could serve as a second-line modality also for the assessment of the extra spinal portion of the brachial plexus. In our opinion, any merely investigative surgery must remain the last option.

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