J Shoulder Elbow Surg (2019) 28, 1033–1039

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Evaluation of radial nerve continuity early after humeral shaft fracture fixation using high-resolution nerve ultrasonography: a pilot study of feasibility

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Background: This study evaluated the feasibility and reliability of high-resolution ultrasonography (HRUS) of the radial nerve in the early, postoperative period after operative stabilization of humeral shaft fractures.
Methods: This study enrolled patients between September 2015 and April 2018 with a humeral shaft fracture who were assessed with HRUS within 2 weeks after surgery. Based on the ultrasound artifacts, the examiners subjectively defined quality of ultrasound as "bad" or "good." The cross-sectional area of the radial and the posterior interosseous nerve was recorded at predefined locations. The radial nerve was scanned axially in the whole course to identify nerve continuity.
Results: Of 44 patients who underwent operations for humeral shaft fracture, HRUS was used to assess 15 patients at an average 4.8 ± 2.6 days (range, 2-11 days) after surgery. The examiners defined ultrasound quality as "good" in 13 of 15 patients (~87%). Primary radial nerve palsy (RNP) was identified in 3 of the 15 patients, and 4 sustained secondary RNP. Nerve continuity was demonstrated by HRUS in every patient. In patients with RNP, nerve continuity was secondarily confirmed by surgical exploration or functional and electrophysiological recovery.
Conclusion: Early postoperative HRUS of the radial nerve after osteosynthesis of humeral shaft fractures is a feasible and reliable method to identify radial nerve continuity. In case of pathology, this assessment tool can additionally provide valuable information concerning location and etiology of the RNP.
Level of evidence: Level III; Diagnostic Study

Keywords: Humeral shaft fracture; primary radial nerve palsy; secondary radial nerve palsy; high-resolution ultrasound; surgical radial nerve exploration; cross-sectional area

The Ethikkommission Nordwest- und Zentralschweiz (EKNZ) (Swiss Ethical Committee) approved this study on April 23, 2018 (Project-ID 2018-00527).

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1058-2746/$ - see front matter
https://doi.org/10.1016/j.jse.2018.11.042

Humeral shaft fracture–associated radial nerve palsy (RNP) can be primary or secondary. In primary RNP, loss of function is caused by the initial trauma leading to the fracture. In secondary RNP, the treatment, either conservative or operative, is responsible for the loss of nerve function. Aspects in conservative and operative treatment, such as reduction maneuvers or entrapment by fracture callus or osteosynthesis material, can cause damage to the radial nerve.

Primary RNP has been reported in up to 12% of humeral shaft fractures, representing the most common long bone fracture–associated peripheral nerve injury.[17] The rate of secondary RNP due to surgical treatment of humeral shaft fractures ranges between 3% and 16%.[4,6,11,14,21] A recent meta-analysis showed no difference in the incidence of secondary RNP between intramedullary nailing and plate fixation.[12] There is a high spontaneous recovery rate of primary RNP in closed humeral shaft fractures, reported to range from 89% to 95%.[2,17] Several studies suggest similar radial nerve recovery rates in secondary RNP.[17,21,22]

However, the timing and role of surgical exploration of the radial nerve in the treatment of humeral fracture–associated RNP is still being debated, particularly in the case of secondary RNP. Some authors prefer an expectative management due to the high rate of recovery and to avoid further damage to the radial nerve.[8,22] Other authors believe that early surgical exploration of the radial nerve in secondary RNP is mandatory to detect and treat potentially curable neural lesions.[16] From a reconstructive point of view, degeneration of the motor end plate and irreversible muscle atrophy occurs if sufficient reinnervation is not present within 12 to 18 months after the injury.[10] The delay of nerve repair has been identified as one key factor that significantly contributes to the outcome of repaired peripheral motor nerves.[15]

To date, there are limited noninvasive methods for the differentiation of pathologies of the radial nerve directly after trauma. Nerve conduction velocity studies and electromyography can be used to determine the location and extent of nerve damage, and electromyography is helpful to monitor radial nerve recovery after axonal injury or nerve reconstruction. However, these electrophysiological assessments are of limited value until 3 to 5 weeks after the trauma or operation.[3,18]

In 2001, Bodner et al[1] suggested that ultrasound imaging might be useful for accurate evaluation of the radial nerve in patients with nerve palsy associated with humeral shaft fractures. High-resolution ultrasonography (HRUS) can be used to demonstrate with a high specificity and sensitivity structural changes such as swelling, hypoechogenicity, loss of continuity, partial laceration, and formation of a neuroma in peripheral nerves.[7,19] This might also be the case in postoperative HRUS of the radial nerve and could help in characterization and localization of the lesion causing primary as well as secondary RNP.

This study evaluated the feasibility and reliability of HRUS of the radial nerve as a noninvasive assessment tool in the early, postoperative period after operative stabilization of humeral shaft fractures.

Materials and methods

This pilot study investigated the feasibility of HRUS of the radial nerve early after osteosynthesis of humeral shaft fractures. Patient data were retrospectively analyzed. The research was conducted in accordance with the Declaration of Helsinki. All patients gave written consent. This article is written in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[20]

Patient selection

Our institution has routinely performed HRUS of the radial nerve after operative stabilization of humerus shaft fractures since September 2015. Every patient with operative stabilization of a humeral shaft fracture was assessed for eligibility. To evaluate the validity of HRUS early after surgery, patients who received HRUS within 2 postoperative weeks were enrolled in this study. Initially, HRUS of the radial nerve was performed only in patients affected by RNP. Later on, to gain experience in this modality, early postoperative HRUS was also performed in patients without RNP.

Additional data analyzed

Baseline patient and trauma characteristics were analyzed, including sex, age, trauma mechanism (subdivided into high-velocity and low-velocity), fracture location on the humeral shaft (mid-diaphyseal, proximal, or distal one-third of the diaphysis), and fracture complexity according to the Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification (A, B and C type fracture). Surgical procedures (plate or nail osteosynthesis), timing of postoperative HRUS, and electrophysiological data concerning the type and grade of RNP were noted. A severe axonal lesion was defined myographically by acute denervation of at least >2+ (scale: 1+ to 4+), by significant subacute or chronic changes in action potential analysis in cases of delayed examination, or neurographically by a >50% reduction of the distal motor or sensory nerve action potential compared with the unaffected side.

HRUS technique

HRUS of the radial nerve was performed by 1 of 4 examiners. A GE Logiq S8 (GE Healthcare, Waukesha, WI, USA) or a SonoSite X-Porte ultrasound system (SonoSite Inc, Bothell, WA, USA) with a 6- to 15-MHz high-resolution linear array transducer was used. The patients were preferably placed supine or sitting with their elbow flexed at 90° for optimized access to the laterodorsal upper arm. To approach the branches of the radial nerve distal to the elbow crease, patients needed to extend and pronate their forearm.

Data analyzed by HRUS

The examiners subjectively defined quality of ultrasound as “bad” or “good” based on the ultrasound artifacts caused by the amount of adipose tissue, early postoperative wounds, soft tissue swelling, hematoma, or osteosynthesis material. The cross-sectional area (CSA)

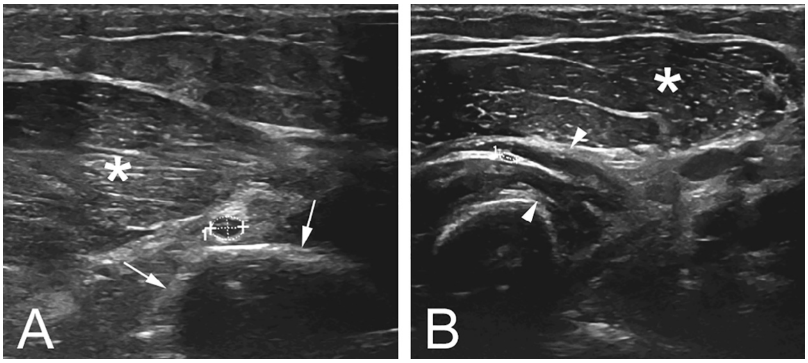

Figure 1 Normal high-resolution ultrasonography (HRUS) findings. (**A**) Radial nerve at the spiral groove (*lateral head of triceps brachii muscle). (**B**) Radial nerve in the supinator canal (⊲ supinator muscle, *brachioradial muscle).

of the radial nerve was recorded at 4 locations: proximal to the spiral groove, at the spiral groove, at the exit of the spiral groove, and in the cubital fossa. The CSA of the posterior interosseous nerve (PIN) was also recorded immediately after bifurcation from the radial nerve and at the entry into the supinator canal. CSA measurements were performed using the elliptical trace tool. Tracing for nerve CSA was inside the hyperintense epineurium. Nerve CSA of >0.10 cm^2 for the radial nerve at the spiral groove and >0.03 cm^2 for the PIN were defined as abnormal based on reference values by Qrimli et al.[13,23] The whole course of the radial nerve was scanned axially to identify nerve continuity (Fig. 1). Verification of radial nerve continuity in patients with RNP was done by surgical exploration or proof of voluntary innervation of the reference muscles by functional or electrophysiological recovery in a follow-up examination.

Rehabilitation and follow-up

The period of clinical and radiologic follow-up included at least 6 weeks and 3, 6, and 12 months after surgery according to the hospital protocol. The rehabilitation protocol consisted of early passive range of motion exercises during the first 3 weeks, followed by 3 weeks of active assisted exercises. After clinical and radiographic follow-up at 6 weeks postoperatively, patients were allowed to start active motion exercises supervised by a physical therapist.

Statistical analysis

Data were analyzed using SPSS Statistics 23.0 software (IBM, Armonk, NY, USA). Descriptive analysis was performed to compare baseline characteristics. The mean ± standard deviation was calculated for continuous parametric data.

Results

Patient selection

There were 44 patients with a humeral shaft fracture who were operated on between September 2015 and April 2018. Within this interval, 17 HRUS examinations were performed of the radial nerve, and 15 of these patients received a HRUS examination within 2 weeks after surgery (Fig. 2).

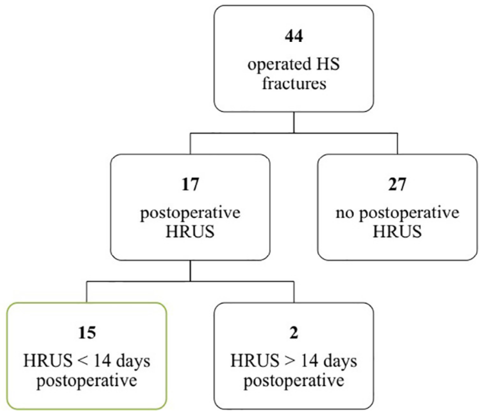

Figure 2 Patient selection between September 2015 and April 2018. *HS*, humeral shaft; *HRUS*, high-resolution ultrasonography.

Patient demographics

The selected 15 patients (7 females and 8 males) were a mean age of 50.6 ± 24 years (range, 15-82 years); of these, 8 patients sustained a high-velocity trauma, and 3 had an open humeral fracture. Twelve fractures were mid-diaphyseal, and 3 were in the distal one-third of the diaphysis. Complexity of the fractures included 8 A, 2 B, and 5 C fractures according to the AO classification.

Surgical procedures involved 13 with plate osteosynthesis and 2 with intramedullary nailing. RNP occurred in 7 patients, with primary RNP identified in 3 patients and secondary RNP in 4. Isolated sensory dysfunction was present in 1 patient, isolated motor dysfunction in 2, and mixed sensorimotor dysfunction in 4. HRUS was performed at an average of 4.8 ± 2.6 days (range, 2-11 days) after surgery by 4 examiners with more than 3 years of experience in nerve ultrasound. Further details regarding the clinical data of the investigated patients are reported in Table I.

The electrophysiological assessment showed severe axonotmesis in 4 of the 7 patients with RNP. The RNP in 2 patients (patients 1 and 10) resolved spontaneously after 6 weeks and did not require electrophysiology (Table II). One

Table I Demographic data of the 15 selected patients

Variable	No. or mean ± SD (range) (N = 15)
Sex	
Female	7
Male	8
Age, yr	50.6 ± 24 (15-82)
Trauma mechanism	
High velocity	8
Low velocity	7
Fracture type	
Open fracture	3
Closed fracture	12
Fracture level	
Middle	12
Distal	3
AO type	
A	8
B	2
C	5
Osteosynthesis	
Plate	13
Nail	2
Approach	
Anterolateral	7
Lateral	1
Posterior	5
RNP	
Primary	3
Secondary	3
RNP type	
Sensory	1
Sensorimotor	2
Motor	4
Time to HRUS, d	4.8 ± 2.6 (2-11)

SD, standard deviation; *AO*, Arbeitsgemeinschaft für Osteosynthesefragen; *RNP*, radial nerve palsy; *HRUS*, high-resolution ultrasonography.

patient (patient 7) with primary sensorimotor RNP refused the electrophysiological assessment (Table II).

Data analyzed by HRUS

HRUS of the radial nerve and PIN was feasible in every patient despite the presence of potential confounding variables mentioned above. The examiners defined ultrasound quality as "good" in 13 of 15 patients (86.6%). In the remaining 2 patients, poor ultrasound quality was limited to the part superior to the spiral groove where the radial nerve could not be depicted.

In 3 of 7 patients with RNP, HRUS revealed a pathologic CSA of the PIN within the supinator canal, indicative of a double-crush phenomenon. This PIN lesion is believed to result from a translation of traction from the relatively mobile main trunk of the radial nerve to a site of reduced mobility of the PIN at the entrance into the supinator canal (arcade of Frohse).[5] Clinically, this finding correlated with isolated motor or mixed sensorimotor dysfunction of the radial nerve. No patients with a secondary PIN lesion presented with isolated sensory dysfunction.

Nerve continuity was demonstrated in every patient. In all patients with RNP, nerve continuity was secondarily confirmed by surgical exploration or functional or electrophysiological improvement.

One patient with a severe polytrauma was intubated from the time of trauma until operative stabilization of the humeral shaft fracture due to serious head injury. After extubation, sensorimotor RNP was diagnosed clinically. Whether the RNP was caused by the initial trauma or by the surgery was unclear. The humeral shaft fracture in this patient was stabilized through an anterolateral approach without surgical visualization of the radial nerve. However, postoperative HRUS showed an injured epineurium in the spiral groove but an intact continuity of the radial nerve. The ultrasonography showed the radial nerve was close to bone fragments without association to osteosynthesis material (Fig. 3, *B*). Therefore the RNP was believed to be of primary origin, and surgical revision was not performed. There was notable clinical improvement of the RNP after 5 and 8 months.

Patients with secondary RNP

In 2 patients with secondary RNP (1 mixed sensorimotor and 1 isolated sensory) after plate osteosynthesis, reoperation was not performed as a result of the HRUS demonstrating an intact radial nerve without compromise by the osteosynthesis material or bone fragments. After 6 weeks, the RNP resolved spontaneously in both patients.

The HRUS of the third patient with secondary RNP demonstrated a pathologic CSA of the radial nerve at the spiral groove, with close proximity to hypoechogenic structures in the humeral shaft, representing fracture fragments or drill holes. The patient returned to the operating room for nerve exploration where nerve continuity was confirmed, and small fracture fragments were removed (Fig. 4). The etiology of the nerve palsy remained unclear but was suspected to be the result of a drill tip injury. After 4 months, there was notable clinical improvement of the RNP, with a full recovery after 8 months.

The fourth secondary RNP was attributed to entrapment of the radial nerve between the humeral shaft and the plate distal to the most proximal screw, identified on HRUS postoperatively. Revision surgery confirmed these findings of the early postoperative HRUS (Fig. 5).

Discussion

This case series proves that early postoperative HRUS of the radial nerve is a feasible and reliable method to verify nerve continuity. In our case series, ultrasound quality of early postoperative radial nerve HRUS was defined as "good" in >85%

Table II Detailed characteristics describing trauma mechanism, fracture type, surgical technique, radial nerve lesion, ultrasonographic and electrophysiologic findings of the 15 patients

Patient	Age (yr)	Trauma energy	AO	Open/ closed fracture	Fixation type	Surgical approach	Lesion type	Clinical	Electrophysiology	HRUS quality	Nerve continuity/ PIN
1	39	Low	A3	Closed	ORIF	Anterolateral	Primary	Sensory	—	Good	Intact
2	77	Low	C1	Closed	ORIF	Lateral	Primary	Motor	Axonotmesis (s)	Bad	Intact/DC
3	22	High	A3	Closed	ORIF	Anterolateral	—	—	—	Good	Intact
4	27	Low	C2	Closed	ORIF	Posterior PT	Secondary	Sensorimotor	Axonotmesis (s)	Good	Intact/DC
5	54	High	C3	Open	ORIF	Posterior PT	—	—	—	Good	Intact
6	15	High	A1	Closed	ORIF	Anterolateral	Primary	Motor	Axonotmesis (s)	Bad	Intact
7	72	Low	A3	Closed	ORIF	Posterior TT	Primary	Sensorimotor	—	Good	Intact
8	84	Low	A1	Closed	ORIF	Posterior PT	Secondary	Sensorimotor	Axonotmesis (s)	Good	Intact/DC
9	80	Low	A2	Closed	Nail	Antegrade nailing	—	—	—	Good	Intact
10	28	High	B1	Closed	ORIF	Anterolateral	Secondary	Sensorimotor	—	Good	Intact
11	43	High	A2	Closed	ORIF	MIPO	—	—	—	Good	Intact
12	29	High	C2	Open	Nail	Antegrade nailing	—	—	—	Good	Intact
13	82	Low	A2	Closed	ORIF	Posterior PT	—	—	—	Good	Intact
14	51	High	B2	Closed	ORIF	MIPO	—	—	—	Good	Intact
15	56	High	C3	Open	ORIF	MIPO	—	—	—	Good	Intact

AO, Arbeitsgemeinschaft für Osteosynthesefragen; *HRUS*, high-resolution ultrasonography; *PIN*, posterior interosseous nerve; *ORIF*, open reduction and internal fixation; *DC*, double crush; *PT*, paratricipital approach; *TT*, transtricipital approach; *MIPO*, minimal invasive plate osteosynthesis; *s*, severe.

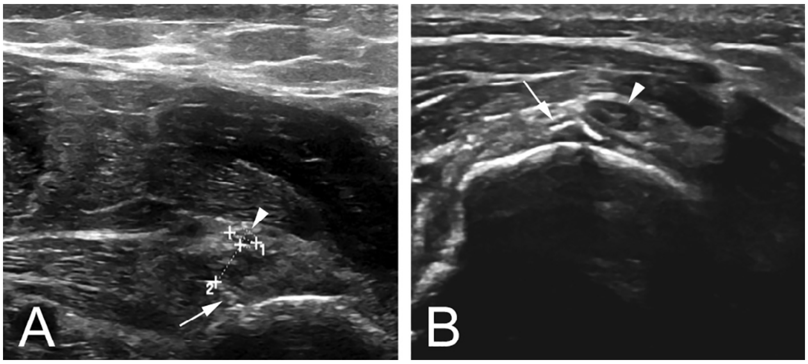

Figure 3 (**A**) High-resolution ultrasound shows close proximity of the radial nerve (◅) to an osteosynthesis screw (→) with distance mesurement between the 2 structures. (**B**) Radial nerve (◅) with adjacent bone fragment (→).

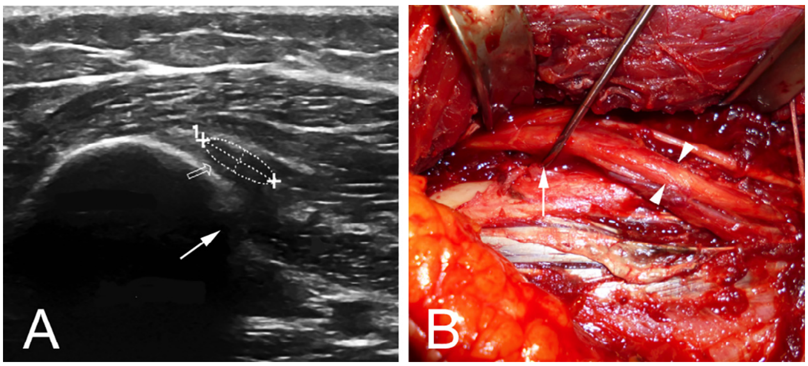

Figure 4 (**A**) Pathologic cross-sectional area of the radial nerve at the spiral groove is close to a drill hole (→). (**B**) Surgical exploration shows the drill hole (→) in relation to the radial nerve (between ◅).

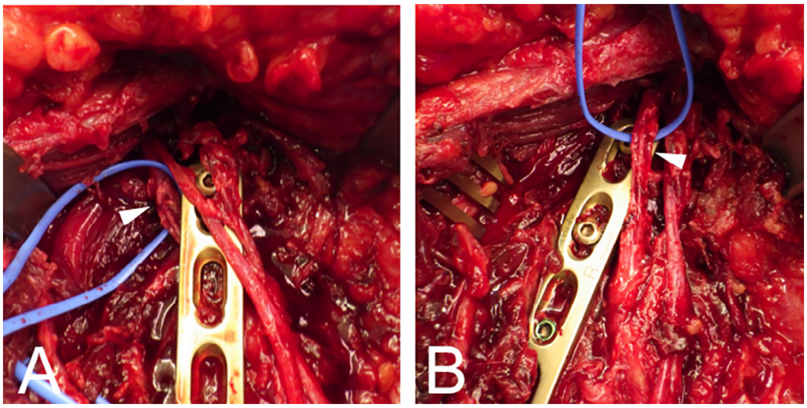

Figure 5 (**A**) Intraoperative finding of the entrapped radial nerve main trunk (*blue loop*, ◃) under the osteosynthesis plate. (**B**) Altered radial nerve main trunk after release from underneath the plate (*blue loop*, ◃).

of the patients. Despite possible ultrasound artifacts, the radial nerve and its continuity were reproducible in every case. In all patients with primary or secondary RNP, nerve continuity was secondarily confirmed by surgical exploration or functional and electrophysiological improvement.

In case of pathology, this method provided valuable information concerning location and etiology of the RNP. HRUS could show close proximity of the radial nerve to bone fragments, drill holes, or osteosynthesis material (Fig. 3). As mentioned above, radial nerve HRUS contributed significantly to the postoperative decision making regarding reoperation in 5 of 7 of our patients with RNP.

Two main aspects of HRUS imaging illustrate the benefit of this modality. First, regardless of the surgical approach, HRUS can provide excellent visualization without further damage to the nerve. This allows the surgeon to choose the optimal surgical approach with focus on fracture stabilization rather than on radial nerve exploration.

Second, higher-grade motor RNP can be caused by a double-crush phenomenon of the PIN. This can explain higher-grade RNP, which does not match the intraoperative finding of the radial nerve main trunk. This double-crush phenomenon is only accessible to HRUS because operative exploration does not include visualization of the PIN. An unexpected swelling of the PIN in patients with proximal radial nerve lesions is common and has been described in other reports.[5,9]

In a systematic review of 397 patients with humeral fracture–associated RNP (primary and secondary) who underwent surgical exploration, 184 patients (46.3%) had an intact nerve without the need for surgical intervention on the nerve itself (impaction by fracture fragments or osteosynthesis material).[17] Considering the feasibility and reliability of early postoperative HRUS of the radial nerve, we believe that the use of HRUS in a targeted manner could reliably identify these patients and thereby significantly reduce the number of unnecessary reoperations. Ideally, radial nerve HRUS should be performed preoperatively to define the location and etiology of a primary RNP. Also in patients without RNP, this modality could provide information regarding radial nerve anatomy and its positional relation to the fracture. This would allow surgeons to plan the optimal approach, osteosynthesis principle (nail or plate), and nerve exploration if necessary. However, the preoperative setting might be difficult to achieve in daily routine. Also this method is only feasible at centers with examiners highly skilled in nerve ultrasonography.

One of the main limitations of the present study lies within the nature of retrospective analyses and the small, selected cohort. Although we observed a highly sensitive detection of radial nerve continuity by early postoperative HRUS, we do not know for certain whether this finding can be extended to a bigger population. Also, ultrasound examinations are known to be dependent on the investigator's experience, and the learning curve should be taken into account. Nevertheless, we showed that it is feasible by 4 examiners with different levels of experience at our hospital.

Clinical and future implications

Given the potential limitations of alternative imaging modalities, such as computed tomography with limited direct visualization of peripheral nerves, and magnetic resonance imaging producing hardware artifacts, HRUS maybe a promising imaging technique for the evaluation of secondary RNP. However, future larger-scale studies with more patients comparing both normal and pathologic radial nerves and correlation with other imaging modalities will be needed to determine the accuracy of HRUS.

Conclusion

Early postoperative HRUS of the radial nerve after osteosynthesis of humeral shaft fractures is a feasible and reliable method to identify radial nerve continuity. In case of pathology, this assessment tool can provide valuable information concerning location and etiology of the RNP.

The use of early postoperative HRUS can potentially provide prognostic information and influence the decision making regarding an eventual need for surgical exploration of the radial nerve.

Acknowledgements

The authors thank Nicole Williams for her linguistic support.

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References

1. Bodner G, Buchberger W, Schocke M, Bale R, Huber B, Harpf C, et al. Radial nerve palsy associated with humeral shaft fracture: evaluation with US—initial experience. Radiology 2001;219:811-6.
2. Bumbasirević M, Lesić A, Bumbasirević V, Cobeljić G, Milosević I, Atkinson HD. The management of humeral shaft fractures with associated radial nerve palsy: a review of 117 cases. Arch Orthop Trauma Surg 2010;130:519-22. http://dx.doi.org/10.1007/s00402-009-0951-4
3. Carter GT, Robinson LR, Chang VH, Kraft GH. Electrodiagnostic evaluation of traumatic nerve injuries. Hand Clin 2000;16:1-12.
4. Claessen FM, Peters RM, Verbeek DO, Helfet DL, Ring D. Factors associated with radial nerve palsy after operative treatment of diaphyseal humeral shaft fractures. J Shoulder Elbow Surg 2015;24:307-11. http://dx.doi.org/10.1016/j.jse.2015.07.012
5. Erra C, De Franco P, Granata G, Coraci D, Briani C, Paolasso I, et al. Secondary posterior interosseous nerve lesions associated with humeral fractures. Muscle Nerve 2016;53:375-8. http://dx.doi.org/10.1002/mus.24752
6. Jawa A, McCarty P, Doornberg J, Harris M, Ring D. Extra-articular distal-third diaphyseal fractures of the humerus. A comparison of functional bracing and plate fixation. J Bone Joint Surg Am 2006;88:2343-7. http://dx.doi.org/10.2106/JBJS.F.00334
7. Kerasnoudis A, Tsivgoulis G. Nerve ultrasound in peripheral neuropathies: a review. J Neuroimaging 2015;25:528-38. http://dx.doi.org/10.1111/jon.12261
8. Korompilias AV, Lykissas MG, Kostas-Agnantis IP, Vekris MD, Soucacos PN, Beris AE. Approach to radial nerve palsy caused by humerus shaft fracture: is primary exploration necessary? Injury 2013;44:323-6. http://dx.doi.org/10.1016/j.injury.2013.01.004
9. Lämmer AB, Schwab S, Schramm A. Ultrasound in dual nerve impairment after proximal radial nerve lesion. PLoS One 2015;10:1-8. http://dx.doi.org/10.1371/journal.pone.0127456
10. Lowe JB 3rd, Sen SK, Mackinnon SE. Current approach to radial nerve paralysis. Plastic Reconstr Surg 2002;110:1099-112. http://dx.doi.org/10.1097/01.PRS.0000020996.11823.3F
11. Mahabier KC, Vogels LM, Punt BJ, Roukema GR, Patka P, Van Lieshout EM. Humeral shaft fractures: retrospective results of non-operative and operative treatment of 186 patients. Injury 2013;44:427-30. http://dx.doi.org/10.1016/j.injury.2012.08.003
12. Ouyang H, Xiong J, Xiang P, Cui Z, Chen L, Yu B. Plate versus intramedullary nail fixation in the treatment of humeral shaft fractures: an updated meta-analysis. J Shoulder Elbow Surg 2013;22:387-95. http://dx.doi.org/10.1016/j.jse.2012.06.007
13. Qrimli M, Ebadi H, Breiner A, Siddiqui H, Alabdali M, Abraham A, et al. Reference values for ultrasonography of peripheral nerves. Muscle Nerve 2016;53:538-44. http://dx.doi.org/10.1002/mus.24888
14. Rommens PM, Kuechle R, Bord T, Lewens T, Engelmann R, Blum J. Humeral nailing revisited. Injury 2008;39:1319-28. http://dx.doi.org/10.1016/j.injury.2008.01.014
15. Ruijs AC, Jaquet JB, Kalmijn S, Giele H, Hovius SE. Median and ulnar nerve injuries: a meta-analysis of predictors of motor and sensory recovery after modern microsurgical nerve repair. Plast Reconstr Surg 2005;116:484-96. http://dx.doi.org/10.1097/01.prs.0000172896.86594.07
16. Schwab TR, Stillhard PF, Schibli S, Furrer M, Sommer C. Radial nerve palsy in humeral shaft fractures with internal fixation: analysis of management and outcome. Eur J Trauma Emerg Surg 2018;44:235-43. http://dx.doi.org/10.1007/s00068-017-0775-9
17. Shao YC, Harwood P, Grotz MR, Limb D, Giannoudis PV. Radial nerve palsy associated with fractures of the shaft of the humerus. A systematic review. J Bone Joint Surg Br 2005;87:1647-52. http://dx.doi.org/10.1302/0301-620X.87B12.16132
18. Thomsen NO, Dahlin LB. Injury to the radial nerve caused by fracture of the humeral shaft: timing and neurobiological aspects related to treatment and diagnosis. Scand J Plast Reconstr Surg Hand Surg 2007;41:153-7. http://dx.doi.org/10.1080/02844310701445586
19. Toros T, Karabay N, Ozaksar K, Sugun TS, Kayalar M, Bal E. Evaluation of peripheral nerves of the upper limb with ultrasonography: a comparison of ultrasonographic examination and the intra-operative findings. J Bone Joint Surg Br 2009;91:762-5. http://dx.doi.org/10.1302/0301-620X.91B6.22284
20. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Int J Surg 2014;12:1495-9. http://dx.doi.org/10.1016/j.ijsu.2014.07.013
21. Wang JP, Shen WJ, Chen WM, Huang CK, Shen YS, Chen TH. Iatrogenic radial nerve palsy after operative management of humeral shaft fractures. J Trauma 2009;66:800-3. http://dx.doi.org/10.1097/TA.0b013e31816142cf
22. Wang X, Zhang P, Zhou Y, Zhu C. Secondary radial nerve palsy after internal fixation of humeral shaft fractures. Eur J Orthop Surg Traumatol 2014;24:331-3. http://dx.doi.org/10.1007/s00590-013-1197-y
23. Won SJ, Kim BJ, Park KS, Yoon JS, Choi H. Reference values for nerve ultrasonography in the upper extremity. Muscle Nerve 2013;47:864-71. http://dx.doi.org/10.1002/mus.23691