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Literature review

High radial nerve palsy

Paralysies radiales hautes

J. Laulan

CHRU de Tours, hôpital Trousseau, services d'orthopédie 1 et 2, unité de chirurgie de la main et du membre supérieur, 37044 Tours cedex 9, France

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ABSTRACT

High radial palsy is primarily associated with humeral shaft fractures, whether primary due to the initial trauma, or secondary to their treatment. The majority will spontaneously recover, therefore early surgical exploration is mainly indicated for open fractures or if ultrasonography shows severe nerve damage. Initial signs of nerve recovery may appear between 2 weeks and 6 months. Otherwise, the decision to explore the nerve is based on the patient's age, clinical examination and electroneuromyography, as well as ultrasonography findings. If recovery does not occur, an autograft is indicated only in younger patients, before 6 months, if local conditions are suitable. Otherwise, nerve transfers performed by an experienced team give satisfactory results and can be offered up to 10 months post-injury. Tendon transfers are the gold standard treatment and the only option available beyond 10 to 12 months. The results are reliable and fast.

Mots clés :
Paralysie du nerf radial
Chirurgie nerveuse
Transferts nerveux
Transferts tendineux

RÉSUMÉ

Les paralysies radiales hautes sont surtout associées aux fractures diaphysaires de l'humérus, qu'elles soient liées au traumatisme initial ou secondaires au traitement. La majorité va récupérer spontanément et l'exploration chirurgicale d'emblée est surtout indiquée si la fracture est ouverte ou si l'échographie montre une lésion sévère du nerf. Les signes d'une récupération spontanée peuvent apparaitre entre 2 semaines et 6 mois. Sinon, la décision d'une éventuelle exploration du nerf sera basée sur l'âge, le suivi clinique et électroneuromyographique, ainsi que sur l'échographie. En l'absence de récupération, une autogreffe n'est indiquée que chez un sujet jeune, avant 6 mois, si les conditions locales sont favorables. Sinon, les transferts nerveux réalisés par une équipe expérimentée donnent des résultats satisfaisants et peuvent être proposés jusqu'à 10 mois. Les transferts tendineux restent le traitement de référence et le seul utilisable au-delà de 10 à 12 mois. Ils donnent des résultats reproductibles et d'obtention rapide.

1. Introduction

High radial nerve palsy (RNP) results from damage to the trunk of the radial nerve, from where it emerges on the posterior cord of the brachial plexus to its division at the elbow. RNP is characterized by the presence of both motor and sensory deficits. Although the sensory deficit has few repercussions, the motor deficit severely compromises wrist function and hand usage [1].

Spontaneous RNP can occur due to radial nerve compression [2] or idiopathic constrictions [3]. However, RNP is most often associated with a humeral shaft fracture (HSF), whether directly related to the initial injury event (primary RNP) or an iatrogenic lesion of the radial nerve (secondary RNP). More than 70% of RNP cases will recover spontaneously, thus the decision between monitoring and surgical exploration (whether primary or secondary RNP) is not straightforward. While the care of HSF is increasingly becoming surgical, conservative treatment associated with RNP monitoring is most often indicated [4,5]. Ultrasonography can be a useful decision aide [6].

In cases of radial nerve lesions, an autograft or palliative treatment – depending on the delay, age and local conditions – are

E-mail address: j.laulan@chu-tours.fr

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to be discussed. Palliative tendon transfer surgery provides reliable results, among the best for this type of surgery [7,8]. Nerve transfers also provide convincing results that can justify their use as long as the muscles are still functional [9].

Given the magnitude of the disability, any restoration of wrist extension and hand opening – even if incomplete – provides a clear functional benefit, including for grip strength [1]. The abbreviations and acronyms used in this review are listed in Table 1.

Table 1
List of abbreviations and acronyms.

APL	Abductor pollicis longus muscle
BR	Brachioradialis muscle
DBRN	Deep branch of the radial nerve
ECRB	Extensor carpi radialis brevis muscle
ECRL	Extensor carpi radialis longus muscle
ECRs	Extensor carpi radialis longus and brevis muscles
ECU	Extensor carpi ulnaris muscle
EDC	Extensor digitorum communis muscle
EDQ	Extensor digiti quinti muscle
EIP	Extensor indicis propius muscle
EMG	Electromyography
ENMG	Electroneuromyography
EPB	Extensor pollicis brevis muscle
EPL	Extensor pollicis longus muscle
HSF	Humeral shaft fracture
FCR	Flexor carpi radialis muscle
FDS	Flexor digitorum superficialis muscle
FCU	Flexor carpi ulnaris muscle
HRP	High radial nerve palsy
LatHTB	Lateral head of triceps brachii muscle
LgHTB	Long head of triceps brachii muscle
LIMS	Lateral intermuscular septum
MCP	Metacarpophalangeal joint
MHTB	Medial head of triceps brachii muscle
PION	Posterior interosseous nerve
PT	Pronator teres muscle
PL	Palmaris longus muscle
RNP	Radial nerve palsy
SBRN	Superficial branch of the radial nerve

2. Anatomy review and surgical approaches

The radial nerve is made up of nerve fibers from the C5 to C8 roots (and sometimes T1) that pass through the posterior cord of the brachial plexus and separate from the fibers forming the axillary nerve in front of the subscapularis muscle [10]. It crosses the inferior axillary space, below the teres major muscle, between the long head of the triceps brachii (LgHTB) and the humerus, oblique distally, dorsally and laterally (Fig. 1). Then, it descends obliquely into the dorsal brachial compartment, against the posterior side of the humerus in the radial sulcus, lateral to the medial head of the triceps brachii (MHTB) and in front of the lateral head of the triceps brachii (LatHTB), accompanied by the deep brachial artery [10]. When it crosses the posterior face of the humerus, it passes 2.5 cm proximal to the tip of the triceps tendon [11]. In the distal and lateral portion of the groove, the LatHTB can have a fibrous arch on its deep surface, which crosses the radial nerve like a bridge and can compress it [2,10] (Fig. 2). Crossing of the lateral intermuscular septum (LIMS), against the humerus, occurs about 10 to 11 cm (range 7.2 to 14 cm) proximal to the lateral epicondyle [12–14]. This is a restriction point for the radial nerve [12]. Finally, the radial nerve descends into the anterior compartment, at the level of the lateral bicipital groove, between the brachioradialis (BR) and the extensor carpi radialis longus (ECRL) muscles laterally and the brachialis and biceps brachii muscles medially (Fig. 3). Anatomical studies show that distal to the LIMS, the radial nerve's position varies greatly [15,16]. It divides in the radial tunnel, 12 cm on average after having crossed the LIMS, into its two terminal branches, the superficial branch (SBRN) and deep branch (DBRN) of the radial nerve.

From a motor standpoint, the radial nerve is the nerve of extension. In the literature, there are discrepancies on the origin of the branches for the triceps [12,13]. It seems however that the main branches emerge proximal to the radial sulcus [10] (Fig. 1). The LgHTB's innervation can come from the axillary nerve, the terminal portion of the posterior cord or be mixed, a combination of axillary and radial [17]. The main branch for the MHTB, which also innervates the anconeus, most often separates from the radial nerve on the medial side of the humerus [10,12]. Then, after having crossed the LIMS, it innervates the BR and ECRL muscles using branches arising directly from the nerve trunk (Fig. 3). In two-thirds of cases, it also gives off one or two branches that innervate the lateral portion of the brachialis muscle [18]. The extensor carpi radialis brevis (ECRB) muscle is innervated by a branch arising most often from the SBRN, but that may emerge from the DBRN in some cases or even directly from the radial nerve [19]. Finally, the DBRN innervates the supinator muscle and the muscles in the dorsal compartment of the forearm: extensor digitorum communis (EDC), extensor carpi ulnaris (ECU), extensor digiti quinti (EDQ), abductor pollicis longus (APL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), and extensor indicis proprius (EIP).

Sensory innervation is ensured by the posterior brachial cutaneous nerve, which arises from the radial nerve in the axillary fossa; the inferior lateral cutaneous nerve which emerges from the radial nerve in the radial sulcus; the posterior antebrachial cutaneous nerve, which emerges from the latter [20] or directly from the radial nerve [14]; and the SBRN which innervates the dorsoradial aspect of the hand.

A lateral approach is the most logical if a surgical treatment is needed [4]. It allows both a wide approach to the distal two-thirds

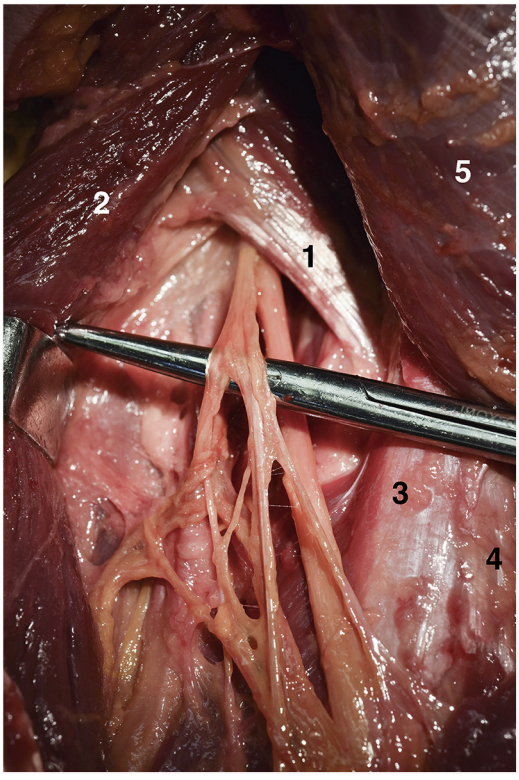

Fig. 1. The radial nerve where it exits the inferior axillary space and provides branches to the triceps brachii. 1- terminal tendon of the teres major muscle; 2- long head of the triceps brachii; 3- humerus; 4- lateral head of the triceps brachii (reflected); 5- deltoid muscle.

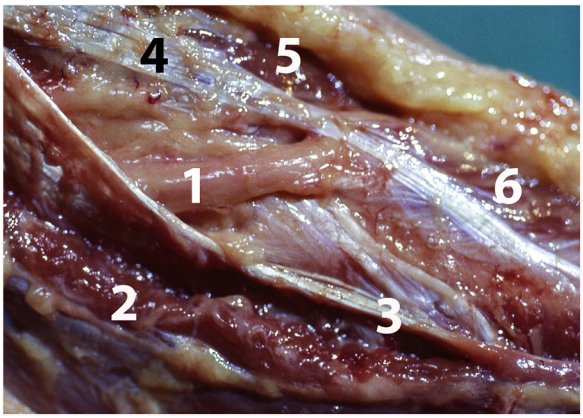

Fig. 2. Passage of the radial nerve from the dorsal brachial compartment to the anterior compartment (right arm, lateral view). 1- radial nerve, 2- lateral head of triceps brachii, 3- fibrous arch of Lotem (reflected posteriorly), 4- lateral intermuscular septum, 5- brachialis muscle, 6- brachioradialis muscle.

of the humerus and satisfactory visual control over the radial nerve, including in the radial sulcus by a proximal extension along the posterior edge of the deltoid muscle [20,21]. With the patient in a supine position, it passes between the muscles of the anterior compartment and the triceps, with the latter reflected from lateral to medial [12]. Locating the superficial nerve branches makes it possible to preserve them and makes it easier to locate the radial nerve, which can be reflected after opening the LIMS [13,20]. The classical, posterior transtricipital approach does not provide access to the distal portion of the radial nerve [21]. Similarly, the anterolateral approach, which is especially useful for proximal fractures, does not completely expose the radial nerve [21].

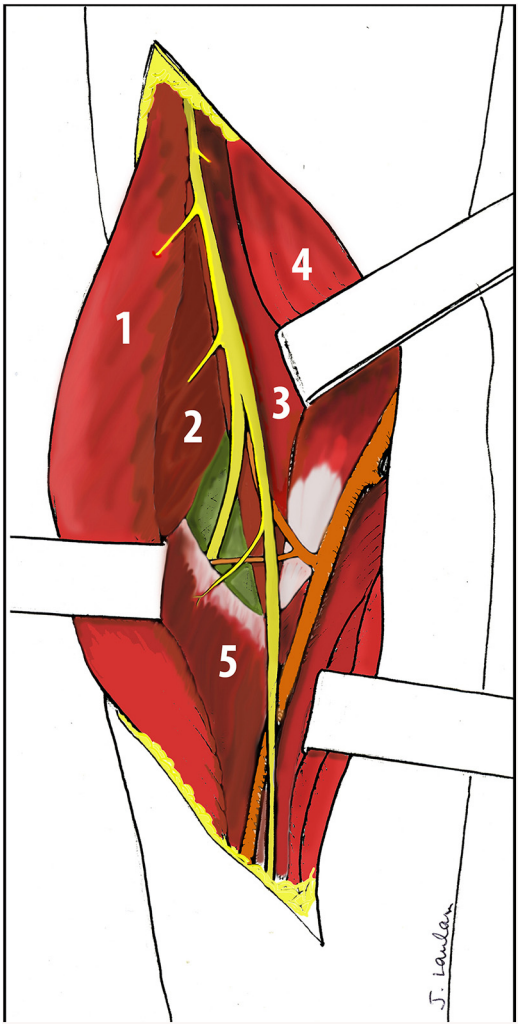

Fig. 3. Radial nerve in the anterior brachial compartment and radial tunnel. Note that the branch for the extensor carpi radialis brevis comes from the superficial branch of the radial nerve. 1- brachioradialis muscle, 2- extensor carpi radialis longus muscle, 3- brachialis muscle, 4- biceps brachii muscle, 5- extensor carpi radialis brevis muscle.

3. Pathophysiology and origin of RNP

3.1. Nerve lesions and their muscular repercussions

The various types of lesions are described in Table 2 using the Seddon and Sunderland classification systems [22,23]. In practice, for radial nerve lesions associated with HSF, it is useful to differentiate between neurapraxia, entrapment, partial lesions and complete lesions [24].

The physiology and trophism of muscles will be altered due to their innervation being suppressed. Early on, edema will be visible on MRI [25]. Starting at 3 weeks, muscular activity at rest appears on electromyography (EMG) in the form of fibrillation potentials. The motor end-plate will start to degenerate, with this process becoming irreversible between 12 and 18 months. Next is muscle degeneration, which becomes irreversible after 18–24 months, with fibrosis and fatty infiltration [26].

3.2. Trauma-induced lesions

The majority of radial nerve palsy cases are due to trauma. The radial nerve is the most damaged nerve during long bone fractures and in upper limb trauma [26,27]. In fact, its trajectory in the posterior compartment of the upper arm and on the lateral side of the humerus, brings it into contact with the periosteum [12,13]. In addition, it is not very mobile where it crosses the LIMS [12]. Thus it is can be injured directly by the fracture and be stretched or even torn due to excessive traction. It can also be compressed between bone fracture fragments.

3.2.1. Palsy related to the initial trauma (primary palsy)

RNP most often occurs in combination with an HSF. HSF makes up 3% to 5% of all fractures with two peaks: young men under 35 years of age and older women above 60 years of age [28,29]. About 12% (range 2% to 18%) of them have radial nerve involvement [5,30,31].

The risk of RNP is greater with open fractures or following high-energy trauma [4,5,29,32] and the risk of severe radial nerve damage is clearly higher [33]. This risk also depends on the location and type of fracture. Fractures of the middle and distal third have a greater risk of radial palsy [5,28,34]. The risk is higher with transverse and spiral fractures, of which 20% are associated with radial palsy [5]. Holstein-Lewis fractures of the distal third of the humerus [35] have the highest prevalence of RNP, impacting 20% to 25% of cases [34,36] (Fig. 4).

However, spontaneous recovery occurs in more than 70% of cases [5], which brings up the problem of deciding whether to perform surgical exploration of the radial nerve even without an HSF indication, especially that most of these fractures are amenable to conservative treatment [28,33,37]. Recovery signs appear in an average of 7 to 8 weeks but can appear as early as 2 weeks after the injury or as late as 6 months [4,5,28].

Lastly, RNP can be due to glass lacerations, knife wounds or gunshot wounds [38,39]. The radial nerve is the nerve most often damaged in times of war [27,40–42].

Table 2
Classification of peripheral nerve injuries.

Seddon classification	Sunderland classification	Nerve injury	Main mechanism electrophysiology	Prognosis treatment
Neurapraxia	First degree	Segmental myelin injury, continuity of axons and connective tissues is preserved, no Wallerian degeneration	Transient ischemia, moderate compression or traction, conduction block, nerve can still be stimulated below the lesion	Spontaneous recoverya few hours to months)
	Second degree	Isolated axonal injury, endoneurial tubes are intact together with perineurium and epineurium	Direct impact, crush injury, traction after 3 to 4 weeks: nerve cannot be stimulated EMG signs of active denervation	Complete recovery typical prognosis linked to distance from effectors; surgery not indicated
Axonotmesis	Third degree	Axons and endoneurium interrupted, perineurium and fascicular arrangement preserved; possible subsequent scarring	Direct impact, crushing, traction after 3 to 4 weeks: nerve cannot be stimulated EMG signs of active denervation	Spontaneous recovery still possible but always partial; surgery may be indicated
	Fourth degree	Only epineurium is preserved; subsequent scarring	Traction injury after 3 to 4 weeks: nerve cannot be stimulated and signs of active denervation	No spontaneous recovery; surgery required
Neurotmesis	Fifth degree	Whole nerve divided	Bladed section, rupture by traction after 3 to 4 weeks: nerve cannot be stimulated and signs of active denervation	No spontaneous recovery; surgery required

EMG: electromyography.

3.2.2. Palsy related to the HSF treatment (secondary palsy)

Radial nerve palsy related to HSF treatment occurs in about 7% (range 2% to 32%) of cases [27,32]. This iatrogenic risk is higher when treating distal third fractures, with a prevalence of 12% to 15% [31,36]. RNP occurs as well with conservative treatment, after simple manipulations, as with open or closed fracture fixation (distal screws associated with intramedullary nailing and external fixator pins, placed percutaneously) [6,15,43] (Fig. 5).

Literature reviews [28,44] comparing plate fixation and intramedullary nailing have found a similar rate of RNP. However, the lesions observed after nailing were more severe [15]. Intraoperative exploration of the nerve also increases the risk of palsy [32,45]. But in this case, it is most often neurapraxia, 90% to 100% of which completely recover spontaneously an average of 2 to 3 months later [30,31]. By comparison, when the nerve is not explored, palsy can be related to more severe lesions with neurotmesis or radial nerve trapped in the fracture site or compressed by the fixation hardware [30,31].

Thus, every surgical approach must include a systematic evaluation of the radial nerve. Opening the LIMS and Lotem's fibrous arch should allow tensionless mobilization of the nerve and limit the risk of neurapraxia. Similarly, percutaneous treatment requires a limited approach and use of protection when drilling for pin or screw insertion, especially that a potential rotational deformity could make the distal position of the radial nerve even less predictable [15,43].

The time to surgery does not increase the risk of radial nerve lesion [31]. But this risk appears to be higher after secondary surgery, during revision for implant failure [31] or after treatment of nonunion [37].

3.2.3. Delayed palsy

Delayed RNP can sometimes appear later after the fracture event and its treatment, with a time frame between 6 weeks and 3 years [46]. It can be observed either after conservative treatment as well as open or closed surgical treatment. These cases of delayed palsy are most often due to compression of the radial nerve by the fracture callus [42]. The radial nerve can also be found trapped in the LIMS and under tension on the end of the distal fracture fragment [46].

3.3. Other causes

Among the other iatrogenic causes, secondary to an invasive procedure, RNP has also been reported after revision total elbow arthroplasty, vein punctures, and intramuscular injections, which cause a proximal lesion with potential involvement of the triceps brachii [27,47,48].

The RNP can be secondary to external compression, with prolonged pressure on the nerve. This can be intraoperative compression related to patient positioning or a tourniquet, such as with automated blood pressure monitors [49,50]. This is also the classical "lover's palsy" mechanism. Neurological damage related

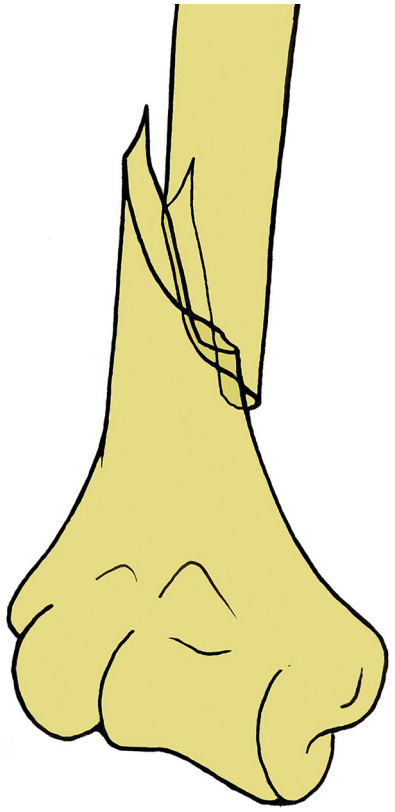

Fig. 4. Drawing of a Holstein-Lewis fracture [35]: spiral fracture of the distal third of the humeral shaft with lateral and proximal displacement of the distal fragment. Both the lateral fracture line and the type of displacement are a potential risk for the radial nerve.

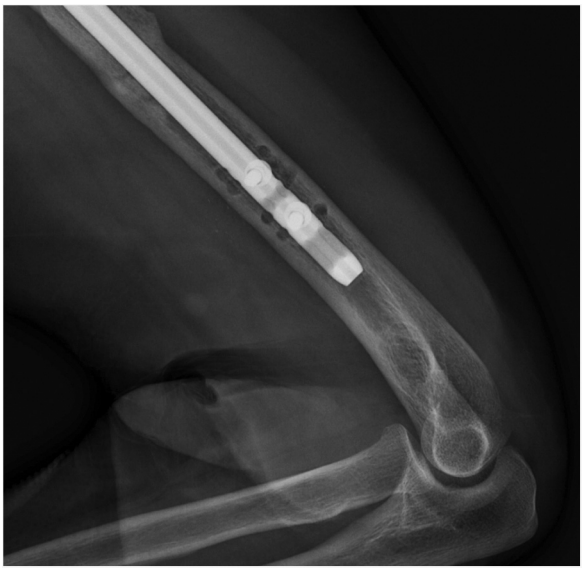

Fig. 5. X-rays after intramedullary nailing of a humeral shaft fracture associated with secondary radial palsy. There are numerous cortical perforations around the end of the nail that project over the theoretical path of the radial nerve.

to use of axillary crutches most often impacts the radial nerve but can also affect multiple trunks; bilateral radial palsy has also been reported [51]. In general, spontaneous recovery occurs in a few weeks, but can take up to 9 months.

The nerve can be compressed by an anatomical structure. Proximal palsy related to compression by the teres major muscle has been reported in a bodybuilder [52]. The nerve can specifically be compressed under the LatHTB arch, with the deficit appearing after intense muscular efforts [2,53]. The possibility of compression between the BR and brachialis muscles has also been reported, along with the possibility of compression related to an accessory BR muscle [54] (Fig. 6).

In the tumor realm, lipomas may occur at the BR muscle and compress the radial nerve trunk, along with humeral chondromas and various intrinsic and extrinsic tumors, including malignant ones [55–59].

RNP has also been reported in the context of infectious, inflammatory or systemic diseases [53,57]. The radial nerve trunk can also be the site of idiopathic constrictions, sometimes many of them [3,60]. The context and histological data suggest an inflammatory origin [3,60]. This can resemble Parsonage-Turner syndrome, and the presence of constrictions can be associated with abnormal MRI findings suggestive of this diagnosis [61].

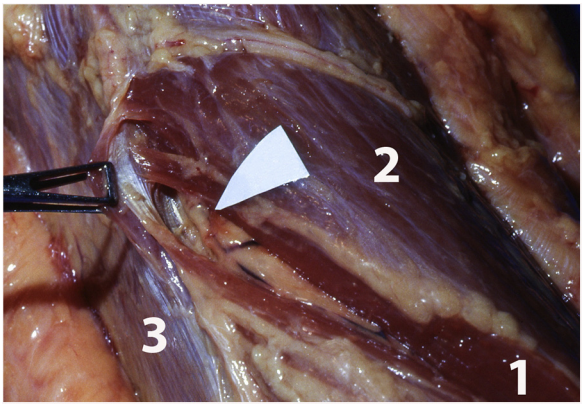

Fig. 6. Anatomical dissection showing an accessory head of the brachioradialis, of which the proximal extension is reflected by the clamp. The radial nerve has an indentation (arrow) over the crossing point between the two structures. 1- brachioradialis muscle, 2- elbow flexors, 3- lateral head of triceps brachii.

4. Clinical

It is vital to look for radial nerve involvement in every patient with an HSF. But this examination can be complicated by the presence of multilevel trauma, or even central nervous system damage, which is not unheard of in the trauma context [26]. If not, the diagnosis is generally easy to make with a combined motor and sensory deficit corresponding to radial nerve trunk systematization, while generally preserving elbow extension.

The motor deficit is obvious with the patient having wrist drop (Fig. 7). A clinical examination will confirm the lack of active extension in the wrist and finger metacarpophalangeal (MCP) joints (detected by keeping the wrist in neutral position) along with loss of thumb abduction and retropulsion. Starting at 5–6 weeks, there is also visible atrophy of the muscles in the posterior compartment of the forearm.

The sensory deficit affects the dorsoradial portion of the hand, particularly the dorsal aspect of the first web space. It can also affect the posterior side of the forearm; however, sensation on the dorsal side of the arm is generally preserved.

In some cases, the deficit is incomplete, with partial preservation of the sensibility. When the motor deficit also affects elbow extension, very proximal damage to the radial nerve is possible. This is particularly suggestive of a lesion to the posterior cord; it is important to assess the deltoid for a motor deficit and the lateral aspect of the shoulder for a sensory deficit.

In some cases, the radial nerve deficit is initiated by pain in the lateral elbow, or even acute, more diffuse pain. This brings up the possibility of nerve compression by Lotem's fibrous arch if the symptoms appeared after a sustained effort, or if not, the possibility of idiopathic constriction [2,3,53,60].

During follow-up visits, the BR and ECRL muscles are tested to look for early recovery. The Tinel sign is used to follow the progression of axonal regrowth, which is said to occur at a speed of about 1 mm per day [62].

5. Additional examinations

5.1. X-rays

These will be used to specify the location and appearance of the fracture and the amount of displacement. In the RNP context, most

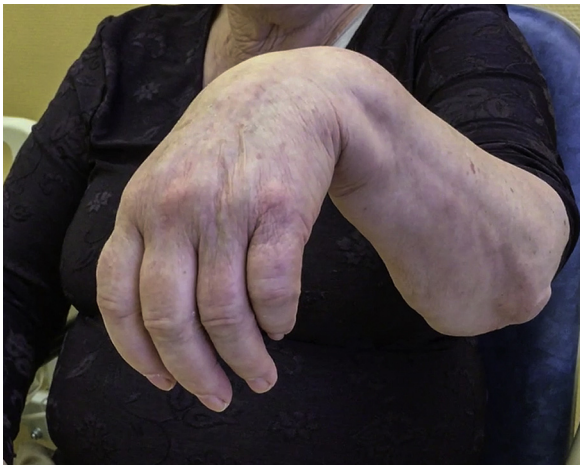

Fig. 7. Example of complete high radial palsy: clinical wrist drop.

of the shaft fractures occur in the middle or distal third of the humerus.

5.2. Electroneuromyography (ENMG)

Initially, it is not possible to differentiate between neurapraxia and axonotmesis until there has been sufficient axonal degeneration. In case of axonal lesions, starting on day 8–10, the amplitude of the motor action potential obtained by stimulation upstream of the lesion decreases; this amplitude is smaller when the axonal loss is greater [26,42]. Only starting at 3–4 weeks can EMG reveal signs of active denervation in the form of electrical fibrillation (abnormal spontaneous activity).

During follow-up visits, the surgeon looks for signs of re-innervation of the proximal muscles (BR and ECRL) in the form of low-amplitude polyphasic potentials. In general, the appearance of EMG signs only slightly precedes the obvious clinical signs of recovery [28].

5.3. High-resolution ultrasonography

In cases of traumatic nerve lesions, ultrasonography is contributive in nearly 60% of cases, helping the surgeon select between monitoring and surgical exploration [63]. It will often help to specify the condition of the radial nerve by analyzing its shape, echogenic structure and trajectory [6].

In severe lesions, it shows a loss of the normal fascicular appearance or even complete disruption of the nerve. In less severe cases, it can show hypoechogenic fascicles due to intraneural edema but with the continuity preserved. In cases of entrapment at the fracture site, the radial nerve's diameter will appear smaller where it is trapped between displaced bone fragments.

Ultrasound imaging facilitates the treatment decision, especially for cases of iatrogenic palsy [6]. It can also contribute to the diagnosis of idiopathic constrictions of the radial nerve [64].

5.4. MRI

In trauma cases, MRI can reveal a flattened nerve, fascicular disorganization or even nerve discontinuity. In compression cases, the radial nerve will look enlarged upstream with increased signal on T2-weighted images, especially near the compression site [57]. Early on, it will show the muscular repercussion of the acute nerve lesion in the form of T2 hyperintensity of the denervated muscles [25]. Later on, it can be used to evaluate muscular trophism and follow the potential re-innervation. In cases of chronic denervation, fatty infiltration is associated with T1 hyperintensity. MRI is less examiner-dependent than ultrasonography, and it is essential for preoperative exploration of tumor-related cases (extrinsic and intrinsic). A 3T MRI makes it possible to localize focal nerve lesions and to diagnose any potential idiopathic constriction [65].

6. Differential diagnosis

The problem of differential diagnosis arises mainly outside the HSF context. Surgeons must not be misled by the obvious character of the motor deficit in the radial territory, thus must systematically look for a radicular or plexus lesion. EMG evaluation of the BR muscle, innervated by C6, is used to differentiate between radial nerve trunk involvement and C7 nerve root involvement. A lesion of the posterior cord of the brachial plexus will have both axillary nerve and radial nerve involvement; however it is sometimes limited to a seemingly isolated RNP that also affects the triceps [61].

In case of isolated involvement of the DBRN, the BR and ECRL innervation is intact along with sensibility. Wrist extension is preserved (ECRL ± ECRB intact) but occurs in radial deviation due to ECU palsy (Fig. 8).

Multiple mononeuropathies, like in amyloidosis, can sometimes appear initially, with radial involvement at the forefront [66]. Similarly, early on, motor neuropathy can be highly suggestive of single nerve trunk damage. Despite the reduced strength, muscle tonus is preserved at this point. The diagnosis is based on ENMG and the detection of anti-GM1 IgM antibodies [67].

Cortical infarct located on the "hand knob" (motor area of the hand, located on the anterior portion of the precentral gyrus) can simulate peripheral damage, especially with loss of wrist and/or finger extension, but it is generally associated with central signs and symptoms [42].

7. Treatment methods

7.1. Conservative treatment

Conservative treatment consists of the patient wearing a brace and undergoing rehabilitation. The brace holds the wrist and provides dynamic extension return under the proximal phalanges. It does not cover the volar side of the hand, which can still be used and thereby prevent exclusion from developing. The aim of rehabilitation is to maintain the passive motion of various joints and to limit the risk of adhesions. Electrostimulation can also be used to maintain muscle trophism. It can only be done in combination with clinical follow-up and ENMG to look for signs of potential spontaneous recovery [68].

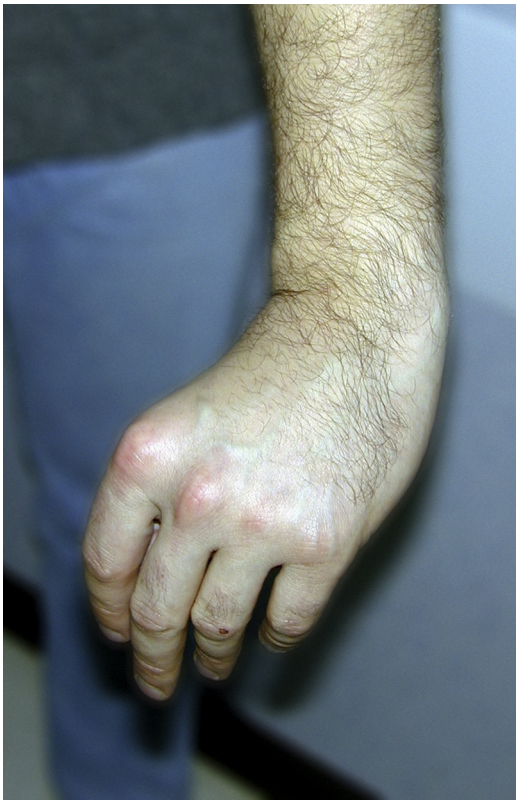

Fig. 8. Example of palsy of the deep branch of the radial nerve. There is paralysis of finger and thumb extension. Wrist extension is preserved but occurs in radial deviation.

7.2. Nerve repair surgery

Many variables will impact the outcome of nerve repair, in particular the level and extent of the radial nerve lesion, the local soft tissue condition, the time to surgery and the patient's age.

Generally, the outcomes of early repair are better than those of secondary repair (> 1 to 2 weeks) [38,41,69]. In the ideal situation, suture repair of a straightforward laceration must be performed within the first 2 or 3 days and followed by at least 3 weeks of immobilization [70]. Later on, if repair is indicated, it must be performed within 6 months [69].

The prognosis of radial nerve suture repair and autograft is better than the one of median and ulnar nerve repair [38,40,71]. In fact, motor fibers predominate in the radial nerve, reducing the risk of their dispersal. In addition, the muscles innervated by the radial nerve have a synergistic action, relatively proximal innervation and somewhat unsophisticated function [38].

7.2.1. Suture repair

The ideal suture technique is epiperineural. It must perfectly align the two nerve ends, be done using 8–0 or 9–0 monofilament as atraumatically as possible with magnification and most importantly, be tensionless [69,70,72]. In practice, with recent injuries, it is often difficult to determine the extent of the nerve contusion and to cut the nerve ends in a healthy area. Thus for radial nerve lesions associated with HSF – given the injury mechanism (crushing, stretching) – the prognosis for primary radial nerve suturing is not good [4]. For straight forward lacerations, the success rate of suture repair ranges from 48% to 80% [41,38]. After low-velocity gunshot wounds, Taha et al. reported good or acceptable recovery in every patient [39].

7.2.2. Autograft

Surgeons are often faced with a gap between the nerve ends, whether in a primary case due to the injury itself, or secondary case due to fibrosis of the nerve ends and their retraction [40]. To avoid suturing the nerve under tension, which negatively affects the outcome, the gold standard is to use an autograft [70,72].

This requires a good quality tissue environment to allow graft revascularization [70] and can be performed in the anterior compartment after having rerouted the radial nerve. The other factors affecting the outcome are the patient's age, graft length, time to surgery and lesion level [41,69].

Roganovic et al. [40] reported useful motor recovery in two-thirds of cases after doing a proximal short (< 4 cm) autograft of 74 radial nerves between 1 and 3.5 months in patients less than 30 years of age with good local conditions. Murovic [38] reported a 60% graft success rate in less strict conditions. An autograft more than 10 cm long or performed beyond 12 months is nearly always associated with failure [41].

7.2.3. Conduits and transformed allografts

Autografts lead to better results than conduits and transformed allograft, which are not indicated for the repair of defects in large nerve trunks [62,69,72].

7.3. Palliative surgery

The aims of palliative surgery are to restore wrist extension, hand opening and thumb extension/abduction [8].

7.3.1. Tendon transfers

This is the benchmark method for palliative treatment of RNP. However, it requires good passive mobility, extensive dissection and 6 weeks of immobilization (Table 3). Tendon transfer principles have been clearly defined in other reviews [7]. Adhesions or even tendon rupture are possible. They restore overall and useful hand function.

Tendon transfers were introduced in the late 19th century when the flexor carpi ulnaris (FCU) was used to revive the EDC [described in 1]. In 1916, Jones described a triple transfer of the pronator teres (PT) on the ECRL and ECRB, FCU on the EDC, and flexor carpi radialis (FCR) on the EIP and EPL. In 1946, Zachary showed the importance of preserving one of the two wrist flexors and chose to use the palmaris longus (PL) to revive the EPL [73].

The motors used to revive finger extension are mainly the FCU [8,74–76] and the FCR [71,77]. The FCU has twice the strength of the FCR. Both have a limited excursion (33 mm), which is theoretically insufficient to restore the EDC's excursion (40 to 50 mm) but is optimized by the tenodesis effect during wrist flexion. Some teams use one tendon of the flexor digitorum superficialis (FDS), which has a 70 mm excursion [1,76]; however, there is a risk of swan-neck deformity in the donor finger. Depending on the aims and other transfers being used, the tendon can either pass through the interosseous membrane (FDS, FCR) or subcutaneously on the ulnar (FCU) or radial (FDS) side of the forearm.

For thumb abduction/extension, some authors also revive the APL and EPB [1] but many others revive solely the EPL by the PL [71,73–76]. The EPL is rerouted subcutaneously to improve the abduction effect of the transferred tendon, although this is mainly done in wrist extension [76]. If the PL is absent, the EPL can be

Table 3
Main palliative techniques used to treat high radial nerve palsy.

	Tendon transfers[a]		Nerve transfers[b]	
Wrist extension (basic techniques and modifications aimed at correcting radial deviation in extension)	PT to ECRL and ECRB (Jones, 1916)	Boyes	PT nerve to ECRL nerve	Garcia-Lopez et al., 2014 (6 cases)
	PT to ECRL, ECRB and ECU	Said		
	PT to ECRB	Riordan; Brand 1; Tsuge; Green		
	PT to ECRB and ECU	Brand 2	FDS nerve to ECRB nerve (± tendon transfer: PT to ECRB)	Ray et al, 2011 (19 cases); Emamhadi (1 case)
	PT to ECRL and ECRB; rerouted ERCL (M3)	Tubiana		
	PT to ECRL and ECRB rerouted ECRL to ECU	Our own technique		
MCP extension (fingers)	FCU to EDC ± EIP	Riordan; Said; Tubiana; Green; Laulan	FCR nerve to PION	All authors
	FCR to EDC ± EIP	Brand; Tsuge		
	FDS to EDC ± EIP	Boyes; Tubiana (variation)		
Thumb extension/ abduction	PL to rerouted EPL (subcutaneous)	Riordan; Said; Tsuge; Green		
	PL to rerouted EPL (through 2nd compartment)	Tubiana; Laulan		

[a] Non-exhaustive list of main techniques described.
[b] Techniques used most often in the context of isolated high radial nerve palsy.

revived by the FCU at the same time as the EDC – with a worse result in terms of abduction [8] – or by a tendon of the FDS [71].

There is broad consensus on using the PT to restore wrist extension. On the other hand, there is some debate between reviving the two ECRs or solely the ECRB [8]. In fact, given the absence of the ECU, wrist extension occurs in radial deviation, which is fatiguing and leads to reduced grip strength [75]. To reduce this problem, Boyes revives the two ECRs but preserves the FCU, on the pretext of a physiological range of motion; however extension still occurs in radial deviation. Brand revives only the ECRB, but this does not correct the radial deviation tendency [8,76]. He later proposed reviving the ECRB and ECU simultaneously using the PT [77]. Said revives the two ECRs and the ECU using the PT [75]. In 1985, Tubiana proposed centralizing the ECRL insertion on the ulnar side of the base of the 3rd metacarpal [76].

Our preferred technique (Fig. 9) is inspired by the "standard" technique [8,74,76] but also revives the ECU using the ECRL [78]. The FCU is rerouted on the ulnar side of the forearm and then anchored to the EDC and EIP. The PT is anchored on the two ECRs, then the ECRL is rerouted and sutured to the ECU tendon. This method allows for finer adjustments to balance the extension axis of the wrist under the action of a single motor (PT) than the variations described by Brand and Said [75,77]. Lastly, the PL is anchored to the EPL, which has been rerouted into the 2nd compartment, which was vacated by ECRL harvesting [76]. This position of the EPL tendon restores more physiological abduction

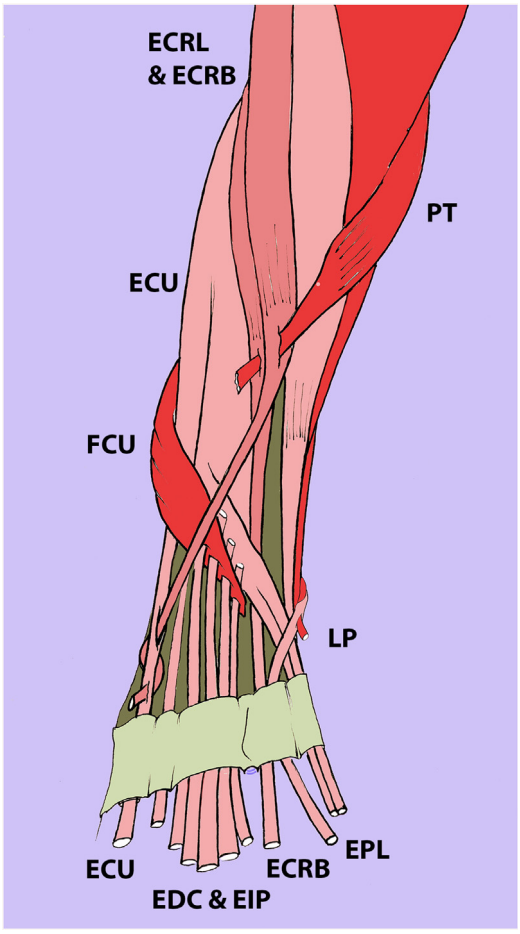

Fig. 9. Drawing of tendon transfers. The EDC and EIP are revived by the FCU. After reviving the two ECRs, the ECRL is rerouted on the ECU to balance out wrist extension. The EPL is rerouted in the 2nd extensor compartment and anchored to the PL tendon.

than a subcutaneous path and the outcome remains acceptable if, when there is no PL, the EPL is also revived with the FCU.

7.3.2. Nerve transfers

Nerve transfer provides exclusive motor stock near the target muscle, which, relative to an autograft, increases the effectiveness of the re-innervation and reduces the time needed [79] (Table 3). It avoids having to harvest a nerve graft and its related complications [69]. It is likely to restore more physiological function than tendon transfers [9] but it takes longer to occur (9 to 12 months) and it is a more demanding technique. The re-innervation time must be compatible with preserving satisfactory muscular trophism, and in case of failure, there are fewer donors for tendon transfer.

There are only a few studies published about their use in RNP (Table 3). The outcomes appear satisfactory, as long as the procedure is carried out by experienced surgeons [8]. This surgery was advanced the most by Mackinnon's team [9,80]. In practice, their basic procedure consists of transferring an FDS nerve onto the nerve for the ECRB, and the FCR nerve onto the DBRN. They sometimes transfer the PT tendon onto the ECRB to provide immediate stabilization of the wrist while waiting for re-innervation to occur [9]. The procedure was performed starting at 3 months and up to 10 months in one case, with an average of 5.7 months. The outcomes are good in terms of wrist extension, but less consistent for finger and thumb extension, with one-third of cases having a poor outcome. Age does not seem to impact the outcome [80]. There is a moderate but transient deficit in the FDS and FCR muscles, which the FDP and FCU can compensate for, respectively. Use of a synergistic donor (FDS) would facilitate the reintegration of wrist extension function [9,80].

To restore wrist extension, Garcia-Lopez et al. [81] prefer using a branch of the PT to re-innervate the ECRL and reported M4 strength in their 6 cases. Like Ray et al. [80], they transfer the FCR nerve onto the DBRN. While extension initially occurs in radial deviation, it is rebalanced afterwards with re-innervation of the ECU through the DBRN.

In the rare cases where elbow extension is also paralyzed, transferring a fascicle of the ulnar nerve onto the LgHTB nerve appears to be the most relevant technique [82].

8. Indications

RNP associated with a wound in the arm area due to glass or knife laceration requires surgical exploration [70]. In cases of radial nerve involvement, the treatment most often consists of simple epiperineural suture after local debridement. In the context of primary repair of a simple radial nerve laceration in the arm, Murovic [38] reported an 80% success rate when the repair was performed early on and 75% when delayed.

If the RNP occurs in combination with an HSF, the decision is based on the injury context (associated vascular lesion, polytrauma), the local conditions (HSF type and displacement, condition of soft tissues and if surgery is performed, that of the nerve), the time to surgery (which drives the choice between nerve surgery and palliative transfer surgery) and the patient's age (nerve regeneration capacity, functional demands, how quickly function is expected to be restored). The RNP can be primary and present right away, secondary and observed immediately after the HSF, or delayed and appearing later after the HSF and its treatment (Fig. 10).

8.1. HSF with RNP present right away (primary RNP)

There are some indications for immediate surgical care, either related to associated lesions (polytrauma, vascular lesion) or

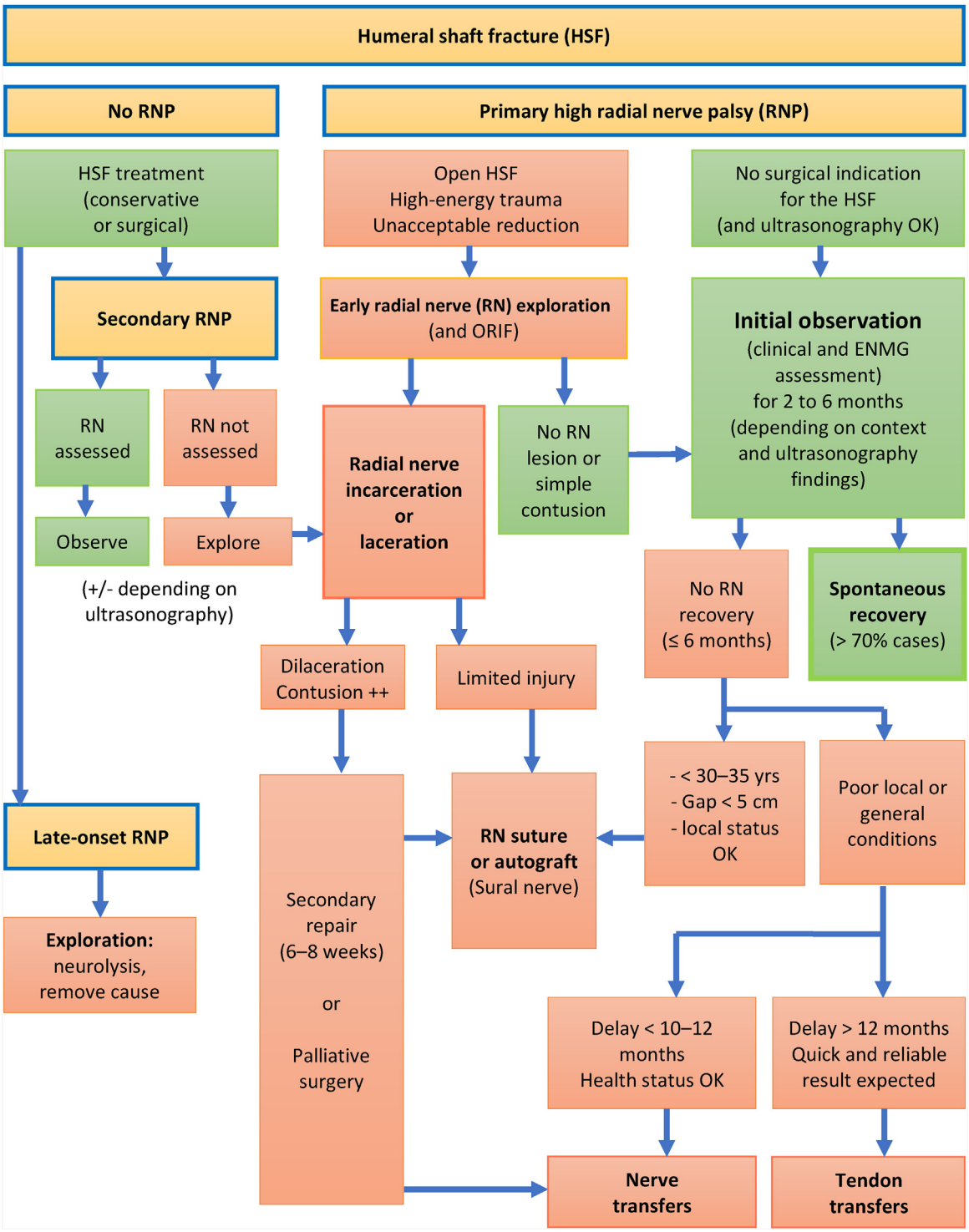

Fig. 10. Management of radial nerve palsy associated with humeral shaft fractures. ENMG: electroneuromyography; HSF: humeral shaft fracture; RNP: high radial nerve palsy; RN: radial nerve.

related to the HSF because there is a significant risk of severe radial nerve damage and poor spontaneous recovery. This is the case with an open HSF or due to a penetrating object, or in middle or distal third fractures resulting from high-energy trauma with significant displacement [4,33,68,83]. In the latter case, ultrasonography can contribute to decision making [33].

If the surgical indication is retained, the presence of RNP makes open fixation preferable to prevent aggravating radial nerve lesions due to blind manipulations [8,24,29]. At this stage, the HSF is acute and, to perform tensionless suture repair in the healthy tissue, the radial nerve can be rerouted through the fracture site (which results in an average 11 mm increase in length) or the bone can be moderately shortened (≤ 3 cm) [5,84]. It is preferable to resort to an autograft instead of repairing the nerve under tension [70].

Most often, the lesion has a poorly defined contusion. The two ends must be secured to each other to prevent retraction and the surgeon will go back 3 to 6 weeks later [4,62,68,70]. In the Murovic

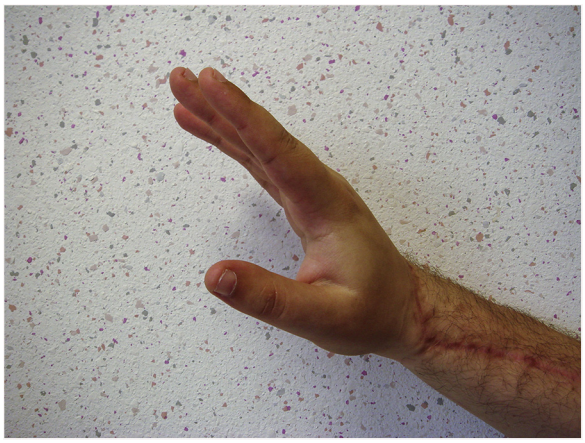

Fig. 11. Outcome 2 months after tendon transfer in a patient who underwent radial nerve resection in the context of excision of a soft tissue tumor in his arm. The goal was rapid recovery of function.

study, the success rate of secondary radial nerve suturing was 69% [38]. If negative prognostic factors are present (dilaceration, extended gap, older patient), early palliative surgery such as nerve or tendon transfer should be discussed.

In closed HSF, it is rare to find a complete radial nerve lesion (except in cases of high-energy trauma) and it is rare for spontaneous recovery not to occur [4,29]. In addition, two literature reviews show that, in HSF patients with RNP, exploring the radial nerve does not improve the recovery rate when compared to patients who are only monitored [5,33]. In a review of literature, Bishop and Ring concluded that monitoring is initially the best option [85]. Thus, if there is no HSF indication and ultrasonography does not find nerve entrapment or transection, there is no reason to operate solely because RNP is present, including for spiral fractures of the distal third of the humeral shaft [45].

If there are no signs of recovery, it is generally accepted that the muscle recovery is compromised if the nerve does not reach the motor end-plate within 12 months [69]. If nerve repair surgery is a possibility, the decision must be made between months 3 and 6, or even earlier according to some authors [26,33,62,70]. At this point, direct suture is rarely feasible and repair – when indicated – most often requires an autograft. In favorable conditions, we can hope for useful recovery in more than 60% of cases [38,40].

However, in cases with large defects, poor local conditions or in older patients, palliative surgery is fully justified at this stage. Based on their experience, Davidge et al. have practically abandoned radial nerve grafts and now favor nerve transfers [9].

Sometimes, the nerve is found to be continuous, with evidence of a less severe or partial lesion. During the surgery, if there are electrophysiological signs suggestive of nerve regeneration, simple neurolysis allows for good recovery in more than 90% of cases [38,69].

8.2. HSF with secondary and delayed RNP

For secondary RNP induced by the HSF treatment, the course of action is not clearly defined. However, if the nerve has not been explored during the initial procedure, if seems justified to explore it, as a radial nerve lesion is common, and Schwab et al. have always found a source for the palsy [30]. The prognosis is related to the time elapsed between the initial procedure and the revision [15]. On the contrary, if the nerve had been checked initially, the complete spontaneous recovery rate is 90% to 100%, thus there is no justification for a revision procedure [30,31]. Ultrasonography can be especially useful in this situation to support the decision [6].

For delayed RNP, there is a compression mechanism (most often the fracture callus) and the surgical exploration indication is definite [46].

8.3. Later on

After failed repair of the radial nerve, the indication for palliative surgery is obvious. In some cases, the patient was only seen later on, and after a 6-month delay, the likelihood of spontaneous recovery is practically zero.

In these cases, if the local conditions are not favorable or if nerve exploration finds a large defect (> 8–10 cm), nerve transfers can be considered up to 10 months after the injury event. The drawback is that it delays the functional recovery even more. Some teams simultaneously perform tendon transfer to stabilize the wrist while waiting for the recovery triggered by the nerve transfer [9,80].

Tendon transfers are the gold standard treatment and are the only option when the patient is seen more than 1 year after the injury event, or in an older patient when a fast result is desired. The outcomes for tendon transfers are among the best in RNP cases (Fig. 11). They provide fast, reliable restoration of useful function, although they do not reproduce the sophisticated physiology of finger extension and active thumb motion [85].

9. Conclusion

Most cases of RNP are related to an HSF or its treatment. Spontaneous recovery is the rule both in primary and secondary palsy cases.

For primary RNP, if there is no surgical indication for the HSF, radial nerve exploration is only justified when spontaneous recovery does not occur. For secondary RNP, when the radial nerve has not been explored during surgery, surgical revision must be contemplated. The surgical indication is absolute for cases of delayed RNP.

Morphological examinations (ultrasonography and MRI) will help detect a potential radial nerve lesion and can contribute to the treatment decision.

The prognosis for suture repair is better for the radial nerve than the ulnar or median nerves: when the time to surgery, local conditions and age are favorable, suture repair or a short autograft of the radial nerve can be indicated. However, some experienced teams have stopped performing autografts given their good results with nerve transfers.

Despite its shortcomings, palliative surgery using tendon transfers is the benchmark method with fast, reproducible results. This is the only treatment option beyond 10 to 12 months post-injury.

Disclosure of interest

The author declares that he has no competing interest.

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