



# Anterior minimally invasive plating osteosynthesis technique (MIPO) for humeral shaft fractures: an anatomical study of neuromuscular structures at risk

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## Abstract

**Objective** The aim of this study was to evaluate the neuromuscular structures at risk during modified anterior minimally invasive plating osteosynthesis technique (Belangero–Livani) for humeral shaft fractures.

**Methods** Eight fresh-frozen human specimens ranging from 38 to 82 years old were used. Specimens were positioned supine with the shoulder in 70° abduction and the forearm in full supination. Anterior minimally invasive plating osteosynthesis technique according to Belangero–Livani technique was performed in each specimen. Under radioscopic control, the plate was introduced in retrograde fashion through the subbrachialis path. Anatomical structures were inspected and different anatomical parameters were measured after dissection at the end of the surgical procedures. Measurements were performed using a high digital caliper. Statistical analysis was performed using the Pearson's correlation coefficient test. A *p* value of < 0.05 was used to define statistical significance.

**Results** There were no macroscopic lesions of myotendinous or neurovascular structures in any specimen. The mean distance between the radial nerve to the distal lateral end of the plate was 8.63 mm (range 4.14–13.83 mm). The mean total length of the humerus was 328.59 mm. We found a significant direct correlation between the total length of the humerus and both specimen height and weight.

**Conclusion** The modified Belangero–Livani anterior MIPO technique for humeral shaft fractures performed in retrograde fashion is safe and useful, without major risk to the soft tissue of the anterior compartment of the arm, including the radial nerve in the lateral intermuscular septum. Intraoperative dissection, avoiding deep lateral retraction on the distal approach, minimizes the risk of radial nerve damage. Strict surgical planning and appreciation for the anatomic landmarks can reduce the risk of damage to neuromuscular structures.

**Level of evidence** Level IV; Case series with no comparison group; Treatment study

**Keywords** Humeral fractures · Diaphysis · Internal fracture fixation · Minimally invasive plate osteosynthesis · Cadaveric study

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## Introduction

Minimally invasive plating osteosynthesis (MIPO) techniques to humeral shaft fractures have been popularized lately with good clinical outcomes and low rate of complications [11, 21]. Cadaveric studies revealed the existence of three extraperiosteal submuscular spaces in the upper arm, which made possible the development of different MIPO techniques for treating these fractures [2, 7, 14]. Noteworthy, the subbrachialis path has been shown particularly interesting, as it anatomically avoids the radial nerve route and allows perfect fitting of the plate over the anterior plane surface of the humerus [16].

Dell’Oca was the first to present his clinical results in 20 multifragmentary proximal and shaft humeral fractures using the MIPO subbrachialis path approach [7, 8]. He introduced the concept of helical plating, in which a large fragment reconstruction plate was twisted 90° and inserted from the superior lateral aspect of the humerus to the distal anterior humerus shaft. No mechanical failures were observed; however, he reported one case of axillary nerve palsy and two cases of transient radial nerve palsy. The author concluded that the helical implant is better indicated in comminuted fractures extending into the proximal part of the humerus [7].

Livani and Belangero described their MIPO technique in 15 patients with humeral shaft fractures using a straight large fragment non-locked plate through the subbrachialis route [17]. Fourteen fractures healed uneventfully, without significant deformity, and patients recovered satisfactory function, with no major complications. Since this publication, Belangero–Livani MIPO technique, either using non-locked or locked plates, has been routinely used as an option in the treatment of humeral shaft fractures, with good results [2, 19, 21, 25, 26]. Although uncommon, complications, such as intraoperative nerve injury and muscle damage, have been described [9, 21]. Consequently, a thorough description of reproducible anatomic landmarks and patient positioning could potentially reduce the risk of soft tissue structures damage during Belangero–Livani MIPO technique.

In 2005, Apivatthakakul et al. performed a cadaveric study to investigate the relationship between the radial nerve and the implant [2]. They found reduced risk of radial nerve injury when the forearm is fully supinated and excessive retraction on the lateral side of the approach is avoided during plate insertion and distal screw fixation. One however, may argue that other soft tissue structures could be damaged when performing the Belangero–Livani MIPO technique, which were not adequately described, mainly in the proximal segment of the approach.

The aim of this study therefore was in a human cadaveric study/to evaluate the risk to the soft tissue structures

of the subbrachialis path, including the radial nerve, during the modified Belangero–Livani MIPO technique performed from distal to proximal humerus.

## Materials and methods

### Cadaveric specimens

Eight fresh-frozen human specimens (16 arms, 8 right and 8 left) were obtained from the Medizinische Hochschule Hannover morgue. Past medical history was reviewed to exclude any history of upper arm pathology. Average age was 66.9 years, ranging from 38 to 82 years. Demographic data of all specimens are presented in Table 1.

The study was performed according to the ethical procedures recommended by the international federation of associations of anatomists (IFAA) [13] and approved by the Institutional Review Board of the Institution.

### Surgical procedure

All procedures were performed in the Medizinische Hochschule Hannover morgue. Two authors (MG and VG) performed all procedures during four scheduled periods of 3 h each. No fracture was produced in the specimens, as this could modify the normal anatomy of the arm. A 12-hole large fragment narrow limited contact dynamic compression plate (LC-DCP®, DPS–J&J Company, Paoli, USA) was re-used in all specimens. Instead of using the originally described proximal to distal Belangero–Livani MIPO technique, in the current study the plate was introduced in retrograde fashion—from distal to proximal (modified Belangero–Livani MIPO technique).

Specimens were positioned supine with the upper limb completely supported on a radiolucent table. C-arm (GE

**Table 1** Demographic data

| Specimen | Initial | Gender | Age (years) | Height (cm) | Weight (kg) |
|----------|---------|--------|-------------|-------------|-------------|
| 1        | HJF     | M      | 38          | 166         | 64          |
| 2        | GHLWG   | M      | 70          | 162         | 51          |
| 3        | PA      | M      | 59          | 172         | 89          |
| 4        | BHD     | M      | 61          | 171         | 93          |
| 5        | GS      | F      | 75          | 160         | 62          |
| 6        | WW      | F      | 81          | 169         | 71          |
| 7        | HD      | M      | 82          | 176         | 93          |
| 8        | HR      | M      | 68          | 165         | 69          |
| Mean     | –       | –      | 66.9        | 167.6       | 74.0        |

F female, M male

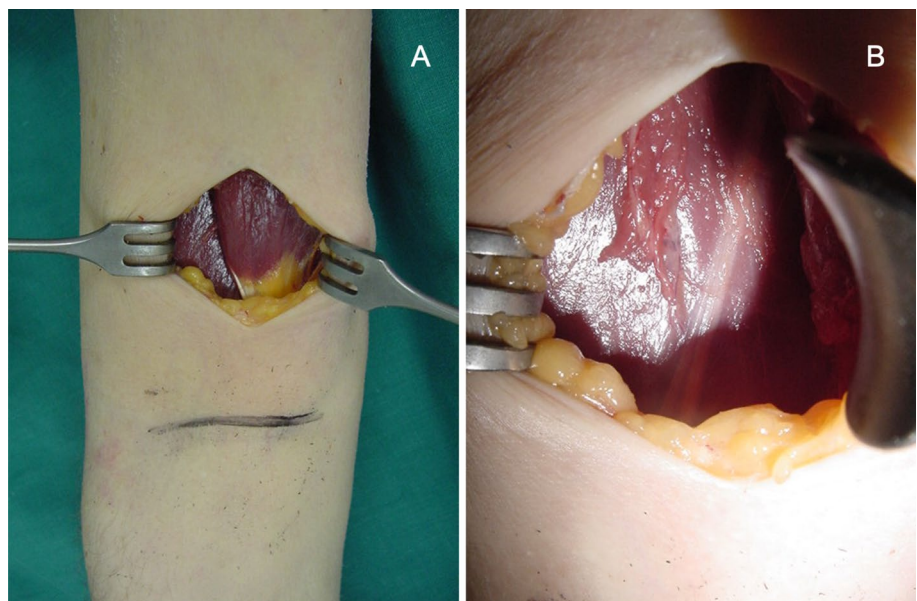
Source: Medizinische Hochschule Hannover

Everview® 7500, General Electric, Boston, USA) was positioned on same side of the operated limb, perpendicular to the axis of the humeral shaft. With the shoulder in 70° abduction and the forearm in full supination, a 4.0 cm distal skin incision was made along the lateral border of the biceps brachii muscle, approximately 3.0 cm proximal to the elbow flexion crease (Fig. 1). Using finger dissection, biceps brachii was retracted medially, which protected the anterior neurovascular bundle, and the musculocutaneous nerve was identified lying on the brachialis muscle (Fig. 2). With a Metzenbaum scissor, the brachialis muscle was split longitudinally along its midline to expose the anterior distal part of the humerus. The medial



**Fig. 1** Specimens were positioned supine with the upper limb completely supported on a radiolucent table, the shoulder in 70° abduction and the forearm in full supination. A 4.0 cm distal skin incision was made along the lateral border of the biceps brachii muscle, approximately 3.0 cm proximal to the elbow flexion crease

**Fig. 2 a** Using finger dissection, biceps brachii was retracted medially, which protected the anterior neurovascular bundle. **b** The musculocutaneous nerve was identified lying on the brachialis muscle

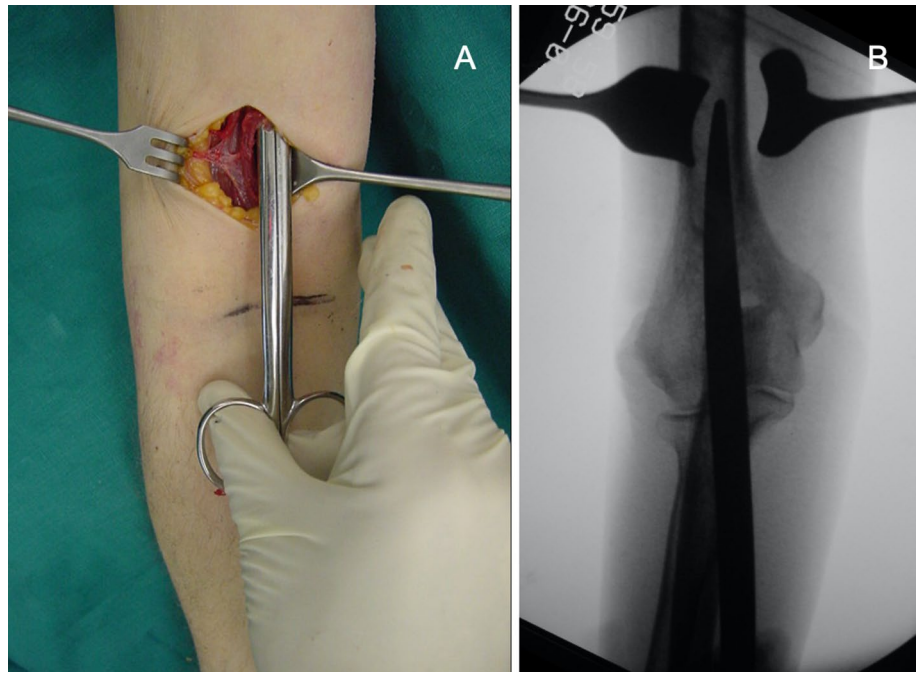


half of this muscle and the musculocutaneous nerve were retracted medially with a shallow Sofield-type double-ended retractor. The other half of the brachialis muscle was retracted laterally with superficial claw-type retractor, preserving the lateral intermuscular septum between this muscle and the brachioradialis muscle [2].

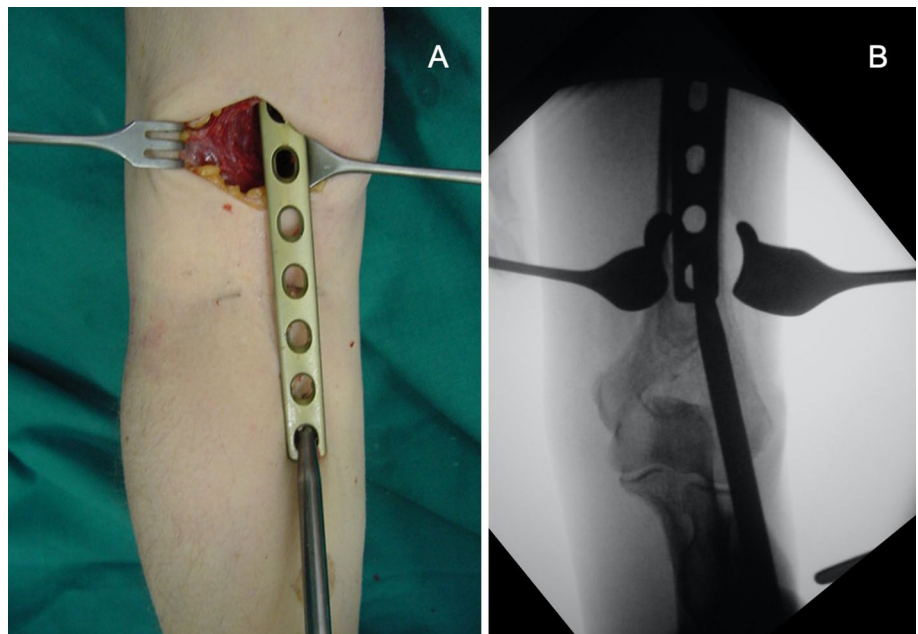
Using scissor dissection, a subbrachialis route was developed from distal to proximal (Fig. 3). Under C-arm control, the plate was introduced in retrograde fashion through the anterior surface of the humerus, up to its proximal part (Fig. 4). Due to shoulder abduction and forearm supination, we noticed a constant path taken by the plate, from central distal to proximal medial. A 4.0 cm proximal skin incision was made in line with the anterior aspect of the acromion, approximately 5.0 cm distal to it. With a Metzenbaum scissor, the interval between the medial border of the deltoid muscle and the pectoralis major muscle was open. The cephalic vein was retracted laterally along with the anterior part of the deltoid muscle (Fig. 5). The tendon of the long head of the biceps brachii muscle was identified with deeper dissection and retracted medially with shallow Sofield-type double-ended retractor. We routinely observed the proximal part of the implant positioned under the pectoralis major tendon, requiring longitudinal splitting along some fibers of the distal lateral border of this tendon to adequately lie the plate on the anterior humeral surface. Plate positioning was checked with C-arm and three 4.5 mm cortical screws were inserted on each side in alternate fashion (Fig. 6). Final fixation was evaluated using fluoroscopic control.



**Fig. 3** **a** With a Metzenbaum scissor, the brachialis muscle was split longitudinally along its midline to expose the anterior distal part of the humerus and a subbrachialis route was developed from distal to proximal. **b** C-arm control demonstrating the subbrachialis route developed with a scissor



**Fig. 4** **a** Under C-arm control, the plate was introduced in retrograde fashion through the anterior surface of the humerus, up to its proximal part. **b** C-arm control demonstrating the plate positioned on the anterior face of the humerus

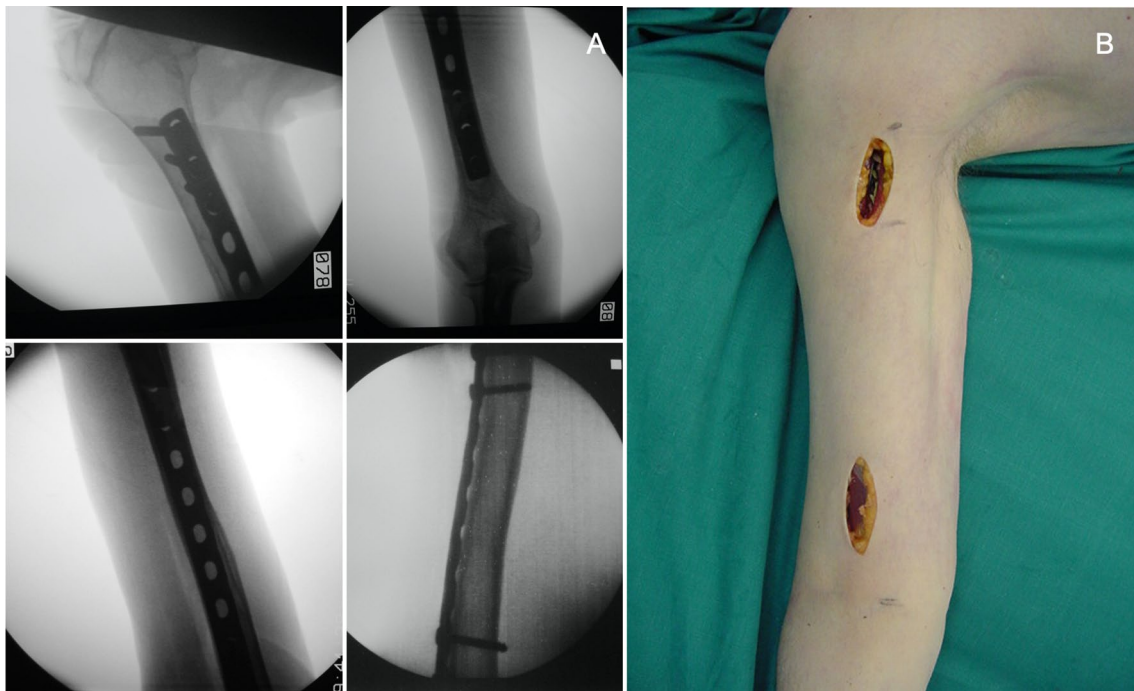
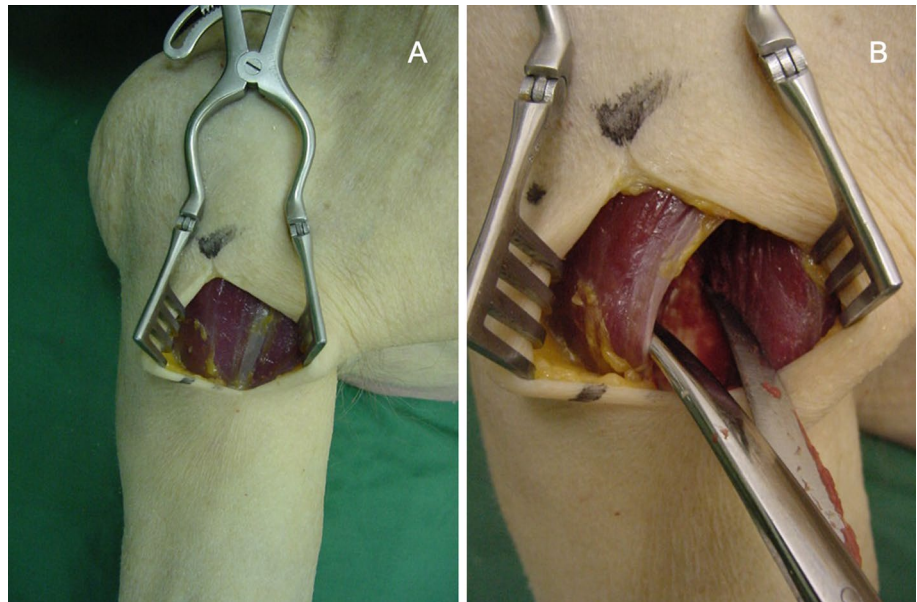


### Surgical dissection and measurements

Dissection was performed in each specimen at the end of the surgical procedure by the same authors who performed the procedures. The proximal incision was extended proximally to complete a deltopectoral approach and distally to meet the distal incision, paying particular attention to identify all neurovascular and myotendinous structures of the anterior compartment of the arm (Fig. 7). The following anatomical parameters were measured:

- Total length of the humerus (TLH),
- Distance between the proximal articular surface of the humerus and the radial nerve at the level of the crossing from the spiral groove into the anterior compartment of the humerus (d Prox-RN),
- Distance between the radial nerve at the level of the crossing from the spiral groove into the anterior compartment of the humerus and the lateral epicondyle of the humerus (d RN-LE),

**Fig. 5** **a** 4.0 cm proximal skin incision was made in line with the anterior aspect of the acromion, approximately 5.0 cm distal to it, and the deltopectoral interval is observed. **b**. With a Metzenbaum scissor, the interval between the medial border of the deltoid muscle and the pectoralis major muscle was opened. The cephalic vein was retracted laterally along with the anterior part of the deltoid muscle

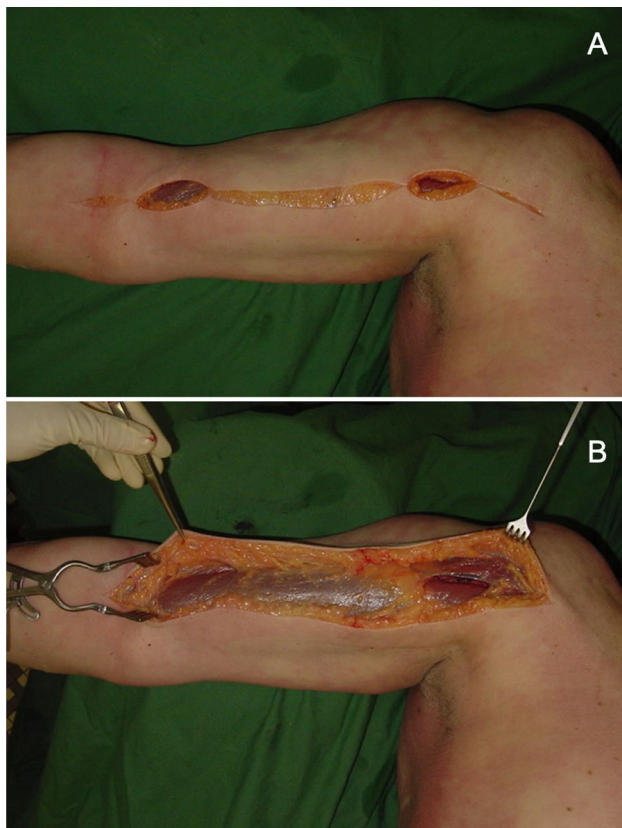


**Fig. 6** **a** Plate positioning was checked with C-arm with three 4.5 mm cortical screws inserted on each side of the plate. **b** Final aspect after fixation. Note the small incisions proximally and distally

- Distance between the lateral epicondyle of the humerus and the distal articular surface of the humerus (d LE-Dist),
- Distance between the distal edge of the plate and the lateral epicondyle of the humerus (d P-LE),
- The smallest distance between the radial nerve and the plate (d RN-P).

Measurements were performed using a high precision digital caliper (Mitutoyo Absolute Digital Caliper, Mitutoyo Corporation, Japan) calibrated to 0.01 mm. Each measurement was repeated three times and only the intermediate value was considered for the statistical analysis. Maximum and minimum values were excluded.





**Fig. 7** **a** The proximal incision was extended proximally to complete a deltopectoral approach and distally to meet the distal incision. **b** Dissection was performed paying particular attention to identify all neurovascular and myotendinous structures of the anterior compartment of the arm

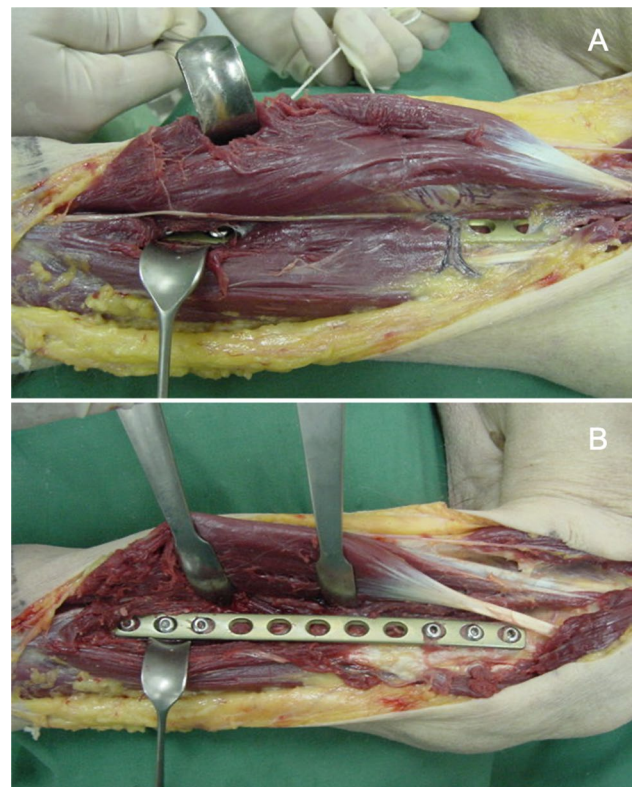
### Statistical analysis

All data were analyzed using SAS® software version 6.04 (SAS Institute, Inc., USA). Pearson's correlation coefficient was used to measure the degree of association between anatomical parameters. A  $p$  value of  $<0.05$  was used to define statistical significance.

### Results

There were no macroscopic lesions of myotendinous or neurovascular structures in any specimen. The anatomical structures inspected were the tendon of the long head of the biceps brachii muscle, the lateral intermuscular septum, the radial nerve, the musculocutaneous nerve, the axillary nerve, the deep brachial artery, and the ascending branch of the anterior humeral circumflex artery (Fig. 8).

The radial nerve was protected by the lateral half of the brachialis muscle and the lateral intermuscular septum. The mean d RN-P was 8.63 mm (range 4.14–13.83 mm),



**Fig. 8** **a** The biceps brachii was elevated. Note the musculocutaneous nerve path and the plate completely protected under the brachialis muscle. A constant observation during dissections was the preservation of the anterior arteriovenous plexus than crosses the humerus transversally. **b** The brachialis muscle was split to demonstrate the perfect fitting of the plate on the anterior face of the humerus

as shown in Table 2. We noticed little variation in the radial nerve position with both shoulder adduction and forearm pronation. The musculocutaneous nerve was identified in all specimens lying on the brachialis muscle and retracted medially with the medial half of the brachialis muscle. The axillary nerve was identified in each specimen only in the proximal extension of the dissection (deltopectoral incision), remaining away from the plate in the subbrachialis path (Fig. 9).

The ascending branch of the anterior humeral circumflex artery was preserved in all specimens when it reaches the intertubercular sulcus to supply the head of the humerus, as the plate was placed in a more medial and distal situation. A constant observation during dissections was the preservation of the anterior arteriovenous plexus than crosses the humerus transversally.

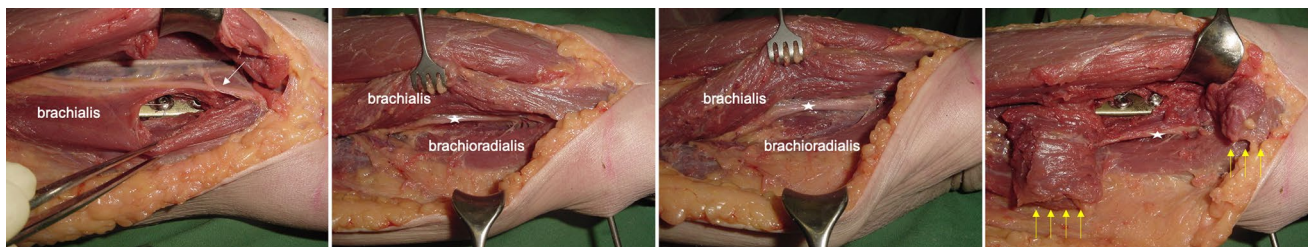
The sum of the d Prox-RN, d P-LE, and d LE-Dist were discrepant by more than 10.00 mm in relation to the TLH only in the first two cases (case 1, right humerus and case 2, left humerus). Two specimens had a difference greater than 10.00 mm between right and left arms

**Table 2** Measurements of anatomical parameters (in mm)

| Specimens | Side | TLH    | d Prox-RN | d RN-LE | d LE-Dist | d RN-P | d P-LE |
|-----------|------|--------|-----------|---------|-----------|--------|--------|
| 1         | L    | 300.15 | 175.10    | 113.50  | 15.05     | 10.30  | 44.16  |
| 1         | R    | 319.00 | 185.31    | 131.35  | 13.69     | 10.24  | 42.93  |
| 2         | L    | 302.91 | 166.17    | 132.63  | 16.74     | 10.09  | 42.38  |
| 2         | R    | 307.84 | 173.53    | 127.38  | 14.31     | 14.26  | 52.73  |
| 3         | L    | 333.57 | 193.79    | 129.31  | 14.47     | 12.73  | 51.24  |
| 3         | R    | 328.41 | 188.25    | 126.83  | 15.47     | 10.00  | 43.46  |
| 4         | L    | 338.19 | 190.86    | 136.86  | 12.29     | 6.41   | 34.47  |
| 4         | R    | 344.05 | 195.73    | 138.05  | 13.37     | 4.14   | 36.20  |
| 5         | L    | 302.04 | 170.18    | 115.08  | 19.47     | 6.36   | 37.23  |
| 5         | R    | 302.31 | 161.89    | 118.10  | 21.72     | 4.44   | 38.86  |
| 6         | L    | 318.52 | 172.33    | 132.87  | 13.93     | 7.16   | 36.84  |
| 6         | R    | 332.29 | 178.15    | 133.22  | 21.23     | 7.71   | 28.21  |
| 7         | L    | 369.90 | 209.27    | 151.12  | 13.83     | 8.45   | 60.20  |
| 7         | R    | 381.30 | 212.31    | 159.52  | 10.66     | 5.88   | 43.40  |
| 8         | L    | 334.97 | 205.92    | 112.21  | 17.42     | 13.70  | 37.31  |
| 8         | R    | 342.00 | 206.88    | 117.10  | 18.50     | 6.14   | 37.31  |
| Mean      | –    | 328.59 | 186.60    | 129.69  | 15.76     | 8.63   | 41.68  |

L left, R right, TLH total length of the humerus, d Prox-RN distance between the proximal articular surface of the humerus and the radial nerve at the level of the crossing from the spiral groove into the anterior compartment of the humerus, d RN-LE distance between the radial nerve at the level of the crossing from the spiral groove into the anterior compartment of the humerus and the lateral epicondyle of the humerus, d LE-Dist distance between the lateral epicondyle of the humerus and the distal articular surface of the humerus, d P-LE distance between the distal edge of the plate and the lateral epicondyle of the humerus, d RN-P the smallest distance between the radial nerve and the plate

Source: Medizinische Hochschule Hannover



**Fig. 9** The radial nerve is completely protected during Belangero–Livani technique. From left to right, note the distal window for the plate on the brachialis muscle belly and the musculocutaneous nerve (white arrow), then the radial nerve (white star) protected in the lat-

eral intermuscular septum between the brachialis muscle and the brachioradialis muscle, and finally the brachialis muscle was divided (yellow arrows) to demonstrate the distance between the radial nerve (white star) and the lateral border of the plate (color figure online)

(cases 1 and 6). The mean TLH was 328.59 mm (range 300.15–381.30 mm) and the mean d RN-LE was 129.69 mm (range 112.21–159.52 mm), which corresponds to approximately 43% of the THL.

There was a significant correlation between the TLH and the d RN-LE ( $r=0.735$ ;  $p=0.001$ ;  $n=16$ ). This means that the higher the TLH, the higher the expected value of the d NR-EL. There is no significant correlation between the TLH and the d RN-P ( $r=-0.230$ ,  $p=0.39$ ;  $n=16$ ) and between the d RN-LE and the d RN-P ( $r=-0.260$ ,  $p=0.33$ ,  $n=16$ ).

There was a significant direct correlation between the specimen height and the TLH on the left side ( $r=0.845$ ;  $p=0.008$ ,  $n=8$ ) and on the right side ( $r=0.851$ ;  $p=0.007$ ;  $n=8$ ). This means that the higher the specimen, the higher the expected value of the TLH (left or right). There was a significant direct correlation between the specimen weight and the TLH on the left side ( $r=0.839$ ;  $p=0.009$ ,  $n=8$ ) and on the right side ( $r=0.764$ ;  $p=0.027$ ;  $n=8$ ). This means that the greater the specimen weight, the greater the expected value of the TLH (left or right).

## Discussion

The modified Belangero–Livani anterior minimally invasive plating osteosynthesis technique to humeral shaft fractures is safe and useful, without major risk to the soft tissue of the anterior compartment of the arm, including the radial nerve in the lateral intermuscular septum. Following strict appreciation to anatomic landmarks and adequate surgical technique, we found no macroscopic lesions of any myotendinous or neurovascular structures. This confirms previous published clinical data using the same technique, showing reduced rate of complications, particularly in reducing the rate of iatrogenic nerve palsy, comparatively to conventional direct reduction surgical techniques [1, 15].

The rate of iatrogenic radial nerve injury has been reported to be as low as 2.8% with MIPO techniques [11, 12, 21]. Anatomically, the radial nerve runs outside the subbrachialis space, which potentially minimizes its damage during the surgical technique. However, it is necessary to avoid both Hohmann and double-ended deep retractors on the lateral part of the distal incision all time, as the nerve is very close to the lateral wall of the distal part of the humerus [7, 16]. In addition, it is recommended to keep the forearm in full supination at all time during plate insertion [2]. Although we did not perform the technique in clinical situation, we also suggest that plate should be introduced in retrograde fashion, as surgeon can have better control of the implant positioning when it runs under the brachialis muscle. We routinely noticed that plate describes a path from central distal to medial proximal in the retrograde fashion and from central proximal to lateral distal in the originally described Belangero–Livani technique, thus increasing the risk of rupture the thin lateral intermuscular septum.

We found a mean distance between the radial nerve and the lateral distal part of the plate to be 8.63 mm, with little variation in its position related to both shoulder adduction and forearm pronation. Advancing the plate in a retrograde fashion, Apivatthakakul et al. found this distance to be on average 3.2 mm with forearm in full supination [2]. These authors observed that the radial nerve moved medially, closer to the distal end of the plate, when the forearm was pronated. Using postoperative ultrasound in 14 patients with humeral mid-shaft fracture, Livani et al. reported this distance to be on average 9.3 mm [18]. They used the Belangero–Livani technique antegrade fashion. These differences reinforce the importance of preserving the integrity of the lateral intermuscular septum at all procedure and raise the question of some factors that can influence the radial nerve route, such as interracial variations and individual anthropometric characteristics, as well as the surgical technique itself.

Interracial variations and individual anthropometric characteristics are frequently investigated in forensic

sciences [22]; however, their clinical implications are equally important in diagnostic and therapeutic decision-making. In order to avoid iatrogenic radial nerve damage, surgeons must understand the anatomy and the anatomical relationships between this nerve and humerus landmarks [6]. Studying healthy individuals, Chen et al. showed that the mean cross-sectional areas of radial nerve are strongly correlated with height and weight, but not with age or side dominance [4]. This observation can be, at least in part, related to the differences observed between our findings and that from other authors [2, 18]. In our study, the mean total length of the humerus was 328.59 mm, with all specimens of Germanic descent. Moreover, we found a significant direct correlation between the TLH and both specimen height and weight, a finding that means that the greater the expected value of the TLH, the higher the specimen and the greater its weight. Although this is not mentioned, we believe Apivatthakakul et al. examined Thai descent and we surely know that Livani et al. investigated Brazilian descent. Other authors found the average TLH to be 287 mm and 302 mm in Chinese and Caucasian specimens, respectively [6, 10].

In spite of a major concern with the risk of injury to the radial nerve, other anatomical structures in the subbrachialis space are potentially at risk during the modified Belangero–Livani anterior MIPO technique to humeral shaft fractures. In the present study, we found no macroscopic lesions of the tendon of the long head of the biceps brachii muscle, the musculocutaneous nerve, the axillary nerve, the deep brachial artery, and the ascending branch of the anterior humeral circumflex artery. Previous studies reported on a relative risk of interference with the long head of the biceps tendon medially when the plate is introduced from a more lateral window [7, 9]. In the Belangero–Livani retrograde fashion technique, this seems to be avoidable as the tendon of the long head of the biceps brachii muscle is always identified with deeper dissection and retracted medially with shallow Sofield-type double-ended retractor before the plate is fixed to the bone.

Attention must be drawn to the musculocutaneous nerve during intermediate dissection of the distal approach. This nerve is usually found deeper to the biceps brachii muscle, lying in the brachialis muscle belly just proximal to the elbow joint. We found it very easy to identify and protect this structure during the procedure, retracting it medially with the medial half of brachialis muscle [5]. Direct injury to this nerve can produce a postoperative numbness sensation on the lateral cutaneous area of the forearm, as the musculocutaneous nerve continues as the lateral antebrachial cutaneous nerve when it exits the space between the biceps brachii and brachialis muscles [5, 20].

This study presents some limitations. Firstly, it is a cadaveric study, which despite providing basis for many clinical



interventions in terms of both diagnosis and therapeutics, represents a limited level of evidence due to interracial variations and individual anthropometric characteristics. However, our study was in agreement with the QUACS scale, which is highly reliable and exhibits strong construct validity in assessing the methodological quality of observational dissection studies [24]. This means that we strictly stated our objective, identified our sample, structured the study protocol, including the process of dissection and the reliability of the observations, thoroughly presented our results, and applied appropriate statistical analysis. Secondly, we used uninjured upper extremities. It is well recognized that skeletal instability may complicate plate placement and alter some anatomical landmarks [3]. However, the production of a fracture could potentially modify the normal anatomy of the arm, making our methodology poorly reproducible. Thirdly, despite we had no macroscopic lesions of myotendinous or neurovascular structures in any specimen, we cannot extrapolate our findings from the cadaveric setting to a real-patient situation. It is well known that neural structures can be damaged following temporary traction or compression during surgery, potentially leading to neuropraxia and transient radial nerve palsy, or affection of sensory branches. Nevertheless, the rate of iatrogenic nerve injury, especially the radial nerve, has been reported to be as low as 2.8% with MIPO techniques [11, 12, 21].

## Conclusion

The modified Belangero–Livani anterior MIPO technique to humeral shaft fractures performed in retrograde fashion is safe and useful, without major risk to the soft tissue of the anterior compartment of the arm, including the radial nerve in the lateral intermuscular septum. Strict surgical planning, including patient positioning, with the shoulder in 70° abduction and the forearm in full supination, and appreciation for the anatomic landmarks potentially reduce the risk of damage to neuromuscular structures. Intraoperative dissection, avoiding deep lateral retraction on the distal approach, minimizes the risk of radial nerve damage. Also, protection of the musculocutaneous nerve and the tendon of the long head of the biceps brachii muscle on the distal and proximal approaches, respectively, is strongly recommended.

**Author contributions** MG and VG were involved in conceptualization, data curation, investigation, and visualization. MG, VG, and CK were contributed to formal analysis, project administration, resources, supervision, and validation. VG was involved in writing—original draft. MG, VG, VSG, WB, BL, PVG, and CK were involved in writing—review and editing. Methodology was contributed by MG, VG, WB, CK. Funding acquisition was contributed by no one.

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## Compliance with ethical standard

**Conflict of interest** Vincenzo Giordano has the following disclosures: Zimmer Biomet: paid consultant and unpaid consultant. Peter V. Giannoudis has the following disclosures: Injury: Editorial or governing board. Christian Krettek has the following disclosures: Traumastiftung: Board or committee member; Springer: Publishing royalties, financial or material support; DFG: research support; AO: research support; BMBF: research support; Else Krömer: research support; Traumstiftung: research support. The remaining authors have nothing to disclose.

**Ethical approval** The study was performed according to the ethical procedures recommended by the international federation of associations of anatomists (IFAA) and approved by the Institutional Review Board of Klinik für Unfallchirurgie–MHH.

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