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Original Research Article

Osteosynthesis of the clavicle after osteotomy in brachial plexus surgery: A biomechanical cadaver study

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ABSTRACT

Objective: The aim of this study was to evaluate and compare the biomechanical effects of locking plate superior and anteroinferior positioning on the osteosynthesis of the clavicles osteotomized obliquely.

Materials and methods: Ten matched pairs of fresh cadaveric clavicles osteotomized through the mid-shaft obliquely were repaired with a titanium 7-hole 3.5-mm reconstruction locking plate in the superior or the anteroinferior position. The maximal failure loads and the displacement of the specimens at 166 N, 183 N, 203 N loads were recorded by the machine in 3-point cantilever bending. Bending failure stiffness was calculated between 10–150 N and 151 N to maximal bending failure loads.

Results: The mean maximal failure load was 396.2 N (SD, 117.3) for superior constructs and 220.1 N (SD, 51.1) for anteroinferior one ($P < 0.05$). There was significant difference in displacement between superior and anteroinferior plated specimens at 183 N (6.3 [SD, 2] vs. 9.9 [SD, 3.6]) and 203 N (6.4 [SD, 0.6] vs. 11.7 [SD, 6.6]) loads; $P < 0.05$). Mean bending failure stiffness between 151 N and maximal loads was 22.6 N/mm (SD, 13.2) for superior plates and 11 N/mm (SD, 9) for anteroinferior plated clavicles ($P < 0.05$).

Conclusions: The superior plating of obliquely osteotomized clavicles with the titanium 7-hole 3.5-mm locking reconstruction plate had a significantly greater biomechanical stability at fixed loads of 183 N and 203 N than the anteroinferior plating in the inferior

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directed cantilever bending. The superior plating osteosynthesis exhibited a significantly greater stiffness from 151 N to maximal bending failure loads as well.

1. Introduction

Brachial plexus lesions are often shocking injuries accompanied by severe long term functional disability and psychological distress [1,2]. The brachial plexus surgery consists of exploration of this anatomic structure, intraoperative nerve monitoring and thorough reconstruction [1–4]. Adequate exposure is essential for brachial plexus surgery success [2–5]. A number of different approaches for the brachial plexus exploration are described in the scientific literature [1–5]. However, the authors express different opinions on the necessity of clavicle osteotomy [1–5]. Profuse bleeding from under the clavicle, upper trunk or supraclavicular lesion, or retroclavicular stretch injuries of the brachial plexus are situations when clavicular osteotomy is recommended [2–4]. Perceptions of biomechanical properties of the clavicle osteosynthesis encourage not to hesitate to osteotomize this bone, facilitating exposure and decreasing surgical time in brachial plexus surgery [4].

The aim of this study is to evaluate and compare biomechanical effects of reconstruction locking plate different location for osteosynthesis of clavicle oblique osteotomy.

2. Materials and methods

The biomechanical study was performed in the Institute of Anatomy, Lithuanian University of Health Sciences. The study protocol was approved by the Regional Biomedical Research Ethics Committee.

In order to avoid the experimental variability associated with clavicles geometries, bone tissue quality determined by the donor age and gender, a matched pairs model has been used in this study. Ten matched pairs of fresh clavicles with no structural deficiencies and any osseous abnormalities were obtained from adult cadavers (seven male and three female) without known metabolic or other bone diseases [6,7]. The mean age of all specimens was 54 years (range, 27–80). The clavicles were stripped of soft tissues [6,7]. All specimens were wrapped in saline saturated towels and stored in tightly sealed plastic bags at −20 °C [6]. The bones were thawed at room temperature for 24 h before testing.

Using simple random sampling, one of the clavicles from each matched pair was plated on the superior aspect with a titanium seven holes 3.5 mm Reconstruction Locking Plate (RLP) (Changzhou Kanghui Medical Innovation Co., Ltd) and the other with an identical implant on the anteroinferior surface [8,9].

Experienced orthopedic trauma surgeons contoured the RLP using standard plate benders to comply with the anatomic center of selected clavicle surface primarily [4,8,9]. Two screw holes, using the technique recommended by the implants manufacturer, were predrilled just medial to the planned osteotomy site [4]. A 3.5-mm self-tapping titanium locking screw (Changzhou Kanghui Medical Innovation Co., Ltd) was inserted before preparation for the second screw would begin [4]. With the plate provisionally seated on the clavicle an oblique osteotomy was planned at the fourth screw hole from the medial end of the plate and marked on the clavicle [4,10]. A lag screw hole was drilled at a 90° angle to the osteotomy line according to the standard AO surgical technique. Then, implants were removed [4]. An oblique mid-shaft osteotomy was created with a 2-mm oscillating saw [11]. A 3.5-mm fully threaded cortical titanium screw (Changzhou Kanghui Medical Innovation Co., Ltd) was introduced perpendiculary to the osteotomy plane as a lag screw for interfragmentary compression. The RLP was replaced and attached to the clavicle using standard surgical technique with three bicortical 3.5-mm self-tapping titanium locking screws (Changzhou Kanghui Medical Innovation Co., Ltd) in the proximal and three bicortical screws in the distal fragments (Fig. 1).

The specimen was positioned by fixing the sternal end in the hole of the square metal tube with epoxy. Each repaired clavicle was then tested in three-points bending by using the universal testing machine [7–9]. A wedge of metal was put under the medial screw closest to the osteotomy and in contact with the specimen [7–9]. A load from the testing machine (Tinius Olsen H25KT) was applied in an inferior direction and perpendicular to the longitudinal axis of the

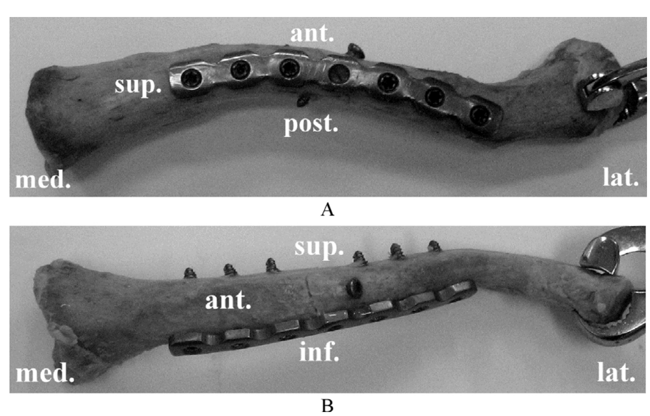

Fig. 1 – Superior (A) and anteroinferior (B) plating osteosynthesis of the osteotomized clavicles with a 7-holes 3.5-mm reconstruction locking plates (sup., inf., ant., post., superior, inferior, anterior, and posterior surface of the specimen, respectively; med., lat., medial and lateral side of the specimen respectively).

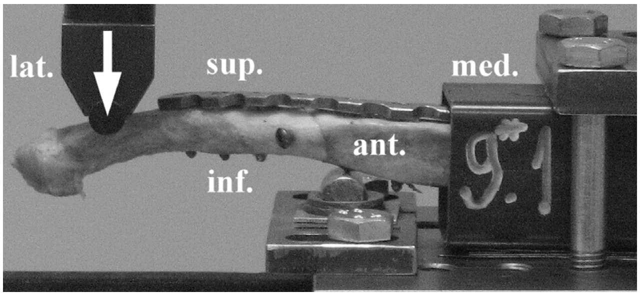

Fig. 2 – Test set-up for clavicle a 3-point cantilever bending (sup., inf., ant., superior, inferior, anterior surface of the specimen, respectively; med., lat., medial, lateral side of the specimen, respectively; arrow, the 3-point cantilever bending direction).

specimen at a rate of 100 mm/min at the point of the acromial end of the clavicle's superior surface which was located at the same distance from the osteotomy site in each matched pair [9]. The inferiorly directed bending of the clavicle simulated the action of the weight of the upper extremity and the shoulder girdle and reflected forces producing the fracture of this bone (Fig. 2).

Loads were delivered until structural failure defined as plate or clavicle breakage or bending to 25 mm of actual displacement [8,9,11,12]. The displacement of the specimens at 166 N, 183 N and 203 N loads was calculated for each group [13]. Bending failure stiffness (N/mm) was calculated as the force per displacement during the failure test between 10–150 N and 151 N to maximal bending failure load for all groups [8,9].

All data were grouped by location of the RLP for descriptive statistics. The statistical analysis was performed by the Mann–Whitney *U*, Wilcoxon, and Fisher exact tests. The statistical power (sp) of the study ($1-\beta$) was calculated in order to avoid a Type II error when the experimental data failed to show differences between osteosynthesis methods. The significance level (α) and false negative rate (β) have been set at 0.05 and 0.2 respectively.

3. Results

Maximal loads to failure were measured for superior and anteroinferior plating osteosynthesis of the clavicle with RLP. Comparison of the maximal loads of the different osteosynthesis methods is described in Table 1.

Superior plating osteosynthesis of the clavicle with RLP could bear an average maximal load of 396.2 N (SD, 117.3). The mean maximal load to failure of anteroinferior plating osteosynthesis was 220.1 N (SD, 51.1). Statistical analysis revealed that the superior plating osteosynthesis had more resistance against cantilever bending than anteroinferior plating ($P < 0.05$). As much as 80% of clavicles repaired with a superior RLP failed via lag screw pullout and fracture of the bone at the osteotomy site when the mean displacement was 16.3 mm (SD, 5.5), whereas 90% specimens plated with anterior–inferior RLP failed in the same manner and average shift inside was 15.5 mm (SD, 6) ($P > 0.05$; sp, 0.1).

Mean displacements were measured at fixed loads for superior and anteroinferior plating osteosynthesis of the clavicle with RLP. Two (20%), three (30%), and four (40%) specimens plated on the anteroinferior aspect with a seven holes 3.5-mm RLP were violated before reaching 166, 183, and 203 N loads, respectively. There were no damaged specimens plated on the superior aspect before reaching the same fixed forces. The data were analyzed without these violated matched pairs of the clavicles (Table 2).

The RLP arrangement had a statistically insignificant effect on the stability of the osteotomized clavicle osteosynthesis at 166 N load ($P > 0.05$; sp, 0.5). Statistical analysis revealed that the superior plating osteosynthesis had more resistance against cantilever bending that anteroinferior plating at 183 and 203 N loads ($P < 0.05$). Significantly more specimens plated on the anteroinferior aspect with a seven holes 3.5 mm RLP were damaged before reaching 183 and 203 N loads also ($P < 0.05$).

The implants location had a statistically significant effect on the stiffness of the osteotomized clavicle repaired with RLP among 151 N and maximal bending failure load ($P < 0.05$). Superior plating osteosynthesis was stiffer than the anteroinferior one (Table 3). Furthermore, statistical analysis did

Table 1 – Ultimate load to failure and displacement of reconstructed specimen.

Specimens	Parameters			
	Superior plating		Anteroinferior plating	
	Maximal load (N)	Displacement (mm)	Maximal load (N)	Displacement (mm)
1	296.4	19.7	251.2	14.5
2	393.6	23.1	193	23.7
3	534.8	25	298	14.2
4	303.6	24	157.4	15.7
5	479.3	25	239.6	12.5
6	408	12.7	175.2	5.4
7	537	12	203.3	25
8	237.2	9.4	281.6	17.3
9	516	17	248.8	11.3
10	256	12.8	153	24.6

Table 2 – Mean displacements of reconstructed specimens at fixed loads.

Load (N)	Parameters			
	Number	Displacement (mm), mean, SD	95% CI for mean	
			Lower bound	Upper bound
Superior plating				
166	8	5.6 (2.1)	3.8	7.4
183	7	6.3 (2)	4.4	8.2
203	6	6.4 (0.6)	5.8	7
Anteroinferior plating				
166	8	7.5 (2.3)	5.6	9.4
183	7	9.9 (3.6)	6.6	13.2
203	6	11.7 (6.6)	4.8	18.6

Table 3 – Bending failure stiffness of reconstructed specimens.

Load (N)	Parameters		
	Bending failure stiffness (N/mm), mean, SD	95% CI for mean	
		Lower bound	Upper bound
Superior plating			
10–150	29.8 (10.7)	22.2	37.5
151–max load	22.6 (13.2)	13.2	32
Anteroinferior plating			
10–150	22 (8.8)	15.8	28.3
151–max load	11 (9)	4.6	17.4

not show that superior plating osteosynthesis was stiffer in comparison with anteroinferior plating between 10 and 150 N loads ($P > 0.05$; sp, 0.55).

Bending failure stiffness between 10–150 N and 151 N to maximal bending failure load for anteroinferior RLP was significantly different ($P < 0.05$). The anteroinferior plating osteosynthesis had lower stiffness at higher than 151 N load force. The same biomechanical effect was not found in the superior plated group ($P > 0.05$; sp, 0.4).

4. Discussion

The transclavicular approach is described as one of the approaches to the brachial plexus [2–4]. Despite several indications, the transclavicular approach has not found dignified popularity [1–5,14]. Perhaps it is related to the tendency of clavicle osteotomies to create nonunion and potential compression of the reconstructed brachial plexus by osseous callus [1]. The standard technique for fusion of a divided clavicle is the internal plate fixation [4,15–17]. This technique provides immediate rigid stabilization and facilitates early mobilization [15–18]. Most commonly the plate is placed at the superior (subcutaneous) aspect of the clavicle [17–19]. The application of the implants in this manner is associated with disturbance of nerve grafts vascularization and this position of the plate leaves the patient with a prominence that can be unsightly, sensitive to pressure or even painful [1,17–19]. An anterior–inferior approach was developed in order to allow inferior implantations of the plate and to avoid these problems, but questions concerning the stability of this osteosynthesis remain [15,16].

Several in vitro biomechanical studies have been undertaken to quantify the effect of locking plate location on the osteotomized clavicle fixation strength in three-points cantilever bending test [8,9,20]. In a study performed by Celestre et al., the mean bending load to failure for superior eight hole 3.5 mm locking contourable dual compression plates was 300 N (SD, 59) compared to 170 N (SD, 9) for anterior–inferior plated clavicles [9]. In a study performed by Robertson et al. mean bending load to failure for superior 8-hole 3.5 mm locking contourable dual reconstruction compression plates was 251 N (SD, 34) compared to 40 N (SD, 4) for anterior–inferior plated clavicles [8]. Another study authors claimed that the superior plating osteosynthesis of the clavicle with 7-hole 3.5 mm RLP could bear an average maximal load of 444.8 N (SD, 102.3) compared to 183.3 N (SD, 11.3) for anterior–inferior plated clavicles [20]. These mechanical experiments indicate that clavicles plated at the superior aspect exhibit significantly higher bending load to failure and bending failure stiffness than those plated at the anteroinferior surface of the bone [8,9,20]. The authors of these studies used a transverse osteotomy model for investigation of the effects of plate location on the stability of midshaft clavicle fractures [8,9,20]. In a three-point cantilever bending the anterosuperior surface of the plated clavicles experiences tensile forces whereas the posteroinferior surface experiences compressive forces [12,20]. As the clavicle, plated at the superior aspect, is loaded in bending the two bony fragments are compressed against each other and this opposition provides the higher construct stiffness [8,9,20]. The authors suggest that without this osseous opposition, which is influenced more by the individual characteristics of clavicle specimen, superior plates would probably fail at loads similar to the anteroinferior plates [8,9,21].

However, the data of the current study revealed that the superior plating osteosynthesis with a seven holes 3.5 mm RLP was more resistance against cantilever bending compared to anterioinferior plating in terms of loads to failure and at fixed force of 183 and 203 N. The superior seven holes 3.5 mm RLP provided the best stiffness among 151 N and maximal bending failure loads.

We hope that the biomechanical data derived from this experimental study may allow surgeons to make more definitive clinical decisions about the selection of locking reconstruction plates and their application for osteosynthesis of the osteotomized clavicle in brachial plexus surgery.

5. Conclusions

Superior plating of obliquely osteotomized clavicles with the titanium 7-hole 3.5-mm locking reconstruction plate had a significantly greater biomechanical stability at fixed loads of 183 N and 203 N than anteroinferior plating in inferiorly directed cantilever bending. The superior plating osteosynthesis exhibited a significantly greater stiffness from 151 N to maximal bending failure loads.

Conflict of interests

The authors state no conflict of interests.

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