Chapter 2
Biomechanics of the Clavicle

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Introduction

The clavicle is an S-shaped bone that acts as the only osseous link between the upper extremity skeleton and the thorax. In animals that do not bear weight on their forelimbs, it is absent. In such animals, the scapula is stabilized to the thorax by numerous powerful muscles. The absence of a clavicle improves running and agility on four limbs. In brachiating animals however, including man, it serves as a solid strut to position the upper limb away from the trunk and enhance more global positioning and use of the limb.

Some consider the clavicle to be expendable. Although children with congenital absence of the clavicle [1] and malunions [2] adapt surprisingly well and patients with tumors or infections treated by clavicular resection sometimes function adequately, adults with malunited clavicles often report difficulty with overhead activities requiring strength or dexterity [3]. Patients with total claviculectomy have decreased strength and patient-reported outcomes in the aclaviculate limbs [4]. It is clear that the evolutionary process has determined an important function for the clavicle and we should always strive to preserve the length and alignment of the clavicle.

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Anatomy

The clavicle is classified as a long bone that is on average 151.8 ± 11.7 mm long, 143.9 ± 8.4 mm long in females, and 160 ± 8.5 mm long in males. They are typically longer if they originate from a male or from the left side of the body [5]. The clavicle is named for its S-shaped curvature, with an apex anteromedially and an apex posterolaterally, similar to the musical symbol clavicular (Fig. 2.1).

The larger medial curvature allows more space for passage of neurovascular structures from the neck into the upper extremity through the costoclavicular interval. The transition from medial to lateral curvature occurs at approximately two-thirds the length of the bone as measured from its sternal end, a site that roughly corresponds to both the medial limit of attachment of the coracoclavicular ligaments and the entrance point of the main nutrient artery of the clavicle.

Males have significantly greater medial curvatures than females, most likely due to their greater size. Similarly, left-sided clavicles tend to be longer and have a greater medial curvature. On the other hand, it appears that the lateral curvature of the clavicle is not affected by either gender or anatomical side. Longer clavicles do not necessarily confer larger lateral curvatures (Table 2.1). The curvature of the IM canal represents the curvature an IM device should be shaped to in order to fit inside properly [5].

The clavicle is made up of dense trabecular bone lacking a well-defined medullary canal. In cross-section, the clavicle changes gradually between an expanded prismatic medial end, a tubular midportion, and a flat lateral aspect. In addition to the variation in cross-sectional shape, the diameter of the clavicle and IM canal experience significant

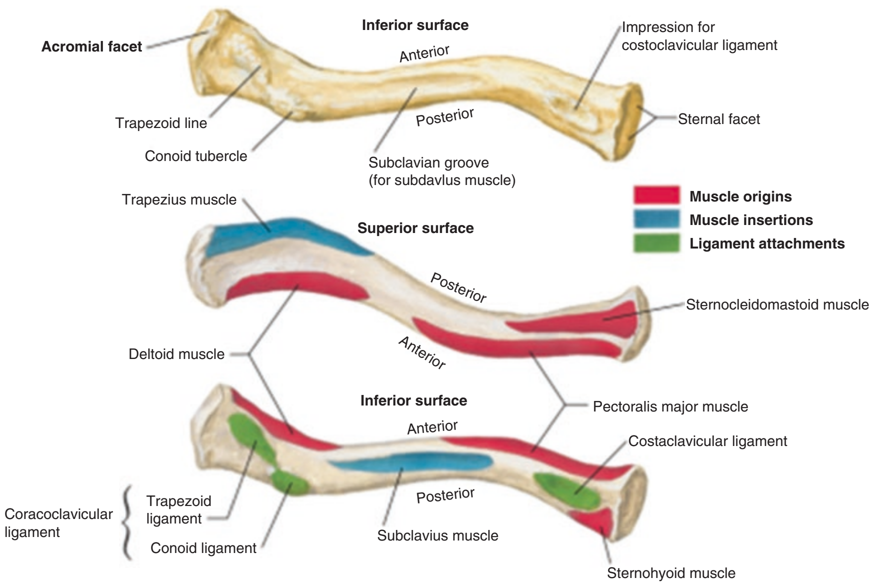

Fig. 2.1 Left clavicle, boney anatomy, and muscle attachments viewed from superiorly and inferiorly

Table 2.1 Radius of curvature and standard deviation of the clavicle when grouped for gender and anatomical side from a 104 sample size clavicle morphometry study

Radius of curvature (mm) ± SD				
	Females—Right	Females—Left	Females	Overall
Medial	83.51 ± 11.82	91.13 ± 15.90	87.54 ± 14.51	91.21 ± 14.4
Lateral	31.86 ± 12.08	34.68 ± 12.57	33.35 ± 12.31	32.51 ± 11.1
	Males—Right	Males—Left	Males	Overall
Medial	93.63 ± 15.03	96.65 ± 11.06	94.99 ± 13.34	91.21 ± 14.4
Lateral	31.51 ± 11.23	31.90 ± 7.77	31.69 ± 9.73	32.51 ± 11.1

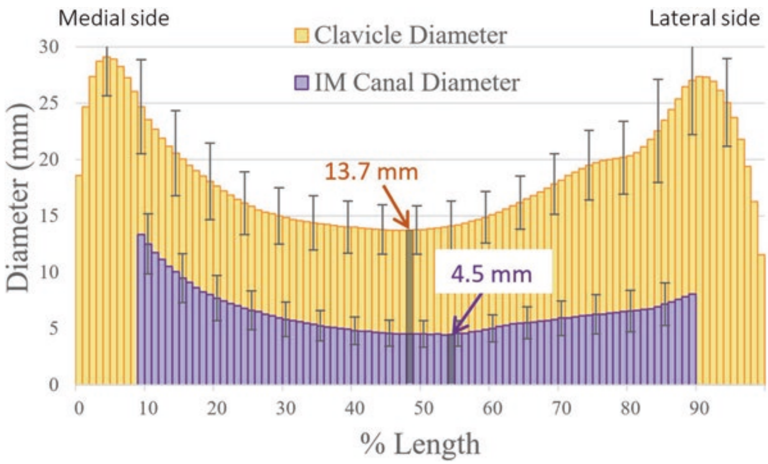

Fig. 2.2 Average clavicle and IM canal diameter as a function of percent clavicle length starting from the medial end from a 104 sample size clavicle morphometry study

change in size. A recent clavicle morphometry study has found that the medial and lateral ends of the bone are the widest regions with an average diameter of 28 mm, while the midportion is significantly narrower, at 13.7 mm. The IM canal also shares this ‘hourglass’ shape, with a smallest diameter of 4.5 mm; however, it is important to note that the location of the narrowest diameter for both clavicle and IM canal occurs at different locations along the midportion (5% clavicle length difference). This offset was observed across all groups (male/female, right/left) and suggests that one may not estimate the location of narrowest region of the IM canal based on external visualization of the clavicle alone (Fig. 2.2). The size and location of the smallest diameter of the IM canal is of special interest as it is the limiting region for IM device design and must be understood for proper implant fit.

Furthermore, clavicle and IM canal are not perfectly congruent. There exists an eccentricity of the IM canal center with respect to the clavicle because cortical thickness and shape are not consistent throughout any given cross-section. This finding also allows us to understand proper IM device fitting inside the canal, as the eccentricity tells us how close the device is to the surface of the bone and how thin the cortex is at any point around it [5] (Fig. 2.3).

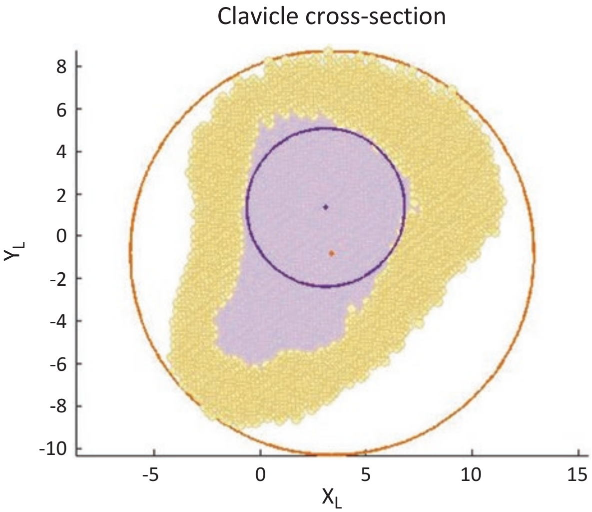

Fig. 2.3 Clavicle cross-section illustrating IM canal eccentricity. The *purple circle* is the largest circular space that could potentially fit an IM device

The above-mentioned peculiarities of the clavicle, namely its curvature, narrowing offset between clavicle and IM canal, and IM canal eccentricity become important when intramedullary fixation of the clavicle is being considered. Since a 3-D morphometric analysis is a requisite for noting these features, a pre-operative CT scan and canal analysis would be warranted in pre-operative planning and implant selection for fracture treatment with an IM device.

As viewed in Fig. 2.1, several muscles attach to the clavicle. The muscles that contribute to shoulder motion are the deltoid, trapezius, and pectoralis. The subclavius muscle serves mainly as a protective layer between the clavicle and the neurovascular structures.

In view of the intimate relationship of the clavicle to the brachial plexus, the subclavian artery and vein, and the apex of the lung, it is surprising that injury to these structures in association with fracture of the clavicle is so uncommon. Brachial plexus palsy may develop weeks or years after injury as a result of compromise of the costoclavicular space by hypertrophic callus, with or without malalignment of the fracture fragments. Narrowing of the costoclavicular space because of malunion or nonunion can also lead to dynamic narrowing of the thoracic outlet. Prolonged compression of vascular structures can likewise be problematic. The course of the neurovascular structures makes it such that medially it is safer to drill superior to inferior and laterally anterior to posterior (Fig. 2.4) [6].

The scapula is a broad thin bone that serves as the origin or insertion for at least 18 different muscles. It also supports the upper extremity through its articulation with the humerus at the glenoid. The glenoid is a narrow, shallow concavity that relies on the surrounding labrum, ligaments, and muscle-tendon units for stability. The acromial and coracoid processes have enlarged during the evolutionary process,

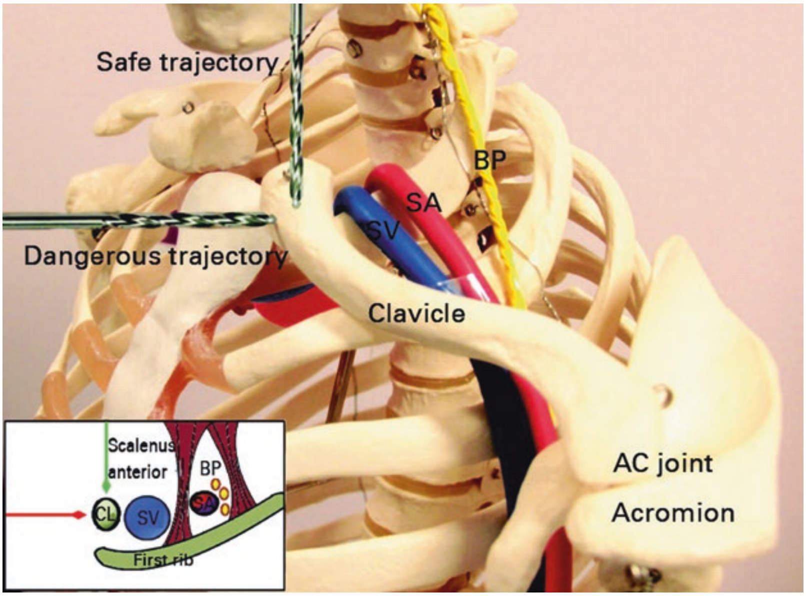

Fig. 2.4 Relationship of neurovascular structures to clavicle and safe drilling trajectories. From Sinha et al.

presumably to provide an origin for more powerful and mechanically efficient upper extremity musculature as well as to give the inherently unstable glenohumeral joint a measure of stability.

Clavicle Contribution to Motion of the Shoulder Girdle

The clavicle articulates on the medial end with the sternum and laterally with the acromion. The sternoclavicular (SC) and acromioclavicular (AC) joints are both diarthrodial articulations (hyaline articular cartilage-covered and synovium-lined mobile joints) with intervening fibrocartilage disks. Both joints lack inherent osseous articular stability and are maintained by strong ligaments. The acromioclavicular joint is unusual in that negligible motion occurs through the joint and yet degenerative arthritis is common, particularly after trauma. The function of the acromioclavicular articulation is unclear. Patients with acromioclavicular or coracoclavicular fusion or coracoclavicular screw fixation have full or nearly full shoulder motion. Most of motion between the shoulder girdle and the axial skeleton must therefore occur at the (SC) joint; a recent study in healthy asymptomatic volunteers documents some motion in the AC joint (19° of scapular tilting maximally) [7]. Motion at the SC joint is commonly thought to be 35° of elevation-depression, 35° of protraction-retraction, and 50° of rotation, as reported by Inman [8].

Ligament-cutting studies in cadavers suggest that the coracoclavicular ligaments limit superior displacement of the clavicle and the acromioclavicular ligaments limit posterior displacement [9]. The capsuloligamentous covering of the acromioclavicular ligament is most stout superiorly. Because one of the complications of distal clavicular excision is posterior displacement of the clavicle with impingement on the scapular spine, many surgeons emphasize preservation of the acromioclavicular ligaments, particularly superiorly.

Forces Seen by the Clavicle and Relation to Fracture

Clavicle fractures are common injuries (2.6–5% of all fractures), with 80% of the fractures occurring in the diaphysis [10]. The chapter will concentrate on the mechanics pertinent to mid-shaft injuries as they are the most common. It is not surprising that the middle third is the most common site of clavicular fracture, since the midportion is the thinnest and narrowest portion of the bone; it represents a transitional region of the bone, both in curvature and in cross-sectional anatomy, which makes it a mechanically weak area, and it is the only area of the clavicle that is not supported by ligamentous or muscular attachments. It is possible that this anatomy was selected during evolution because clavicular fracture protects the brachial plexus during difficult births (shoulder dystocia).

Mechanics of Clavicle Malunion

Clavicular malunion (Fig. 2.5) [11] is emerging as a clinical syndrome identified by shortening, deformity of the shoulder girdle (including the scapula), pain, and fatigue with overhead activity and weakness in strength testing [3, 11, 12]. The forces contributing to persistence or worsening of deformity after fracture include the weight of the shoulder as transmitted to the distal fragment of the clavicle, primarily through the coracoclavicular ligaments, and the deforming forces of the attached muscles and ligaments. The medial fragment is elevated by the clavicular head of the sternocleidomastoid muscle, which inserts onto the posterior aspect of the medial portion of the clavicle. The pectoralis major contributes to adduction and inward rotation of the shoulder.

A study simulating the effect of clavicle shortening on upper extremity muscles found that shortening of the clavicle decreases the moment-generating capacity as well as the total force-generating capacity of the shoulder girdle muscles, especially elevation moments of the upper extremity muscles during abduction and internal rotation [13]. Flexion moments were affected less through physiologic range of motion. Additionally, shortening of the clavicle increases coronal angulation of the clavicle at the sternoclavicular joint thus providing a basic science support to the clinical syndrome of malunion.

Fig. 2.5 Anterior (**a**) and posterior (**b**) view of clavicle malunion. Shortening, drooping of the shoulder girdle and scapular winging of inferior-medial border of clavicle is evident. From Ristevski et al.

A cadaveric study found that shortening of the clavicle produces change to the resting position of the shoulder girdle quite similar to the clinically observed malunions. Moreover, the motion of the shoulder girdle is progressively affected with increasing amounts of shortening [14].

Complications from Clavicle Fractures, Nonoperative Treatment

Traditionally, treatment has been conservative, due to influential historic literature with high rates of healing [15, 16]. More recent literature suggests that the results of nonoperative treatment are worse than what was previously thought. Inferior outcomes and higher risks of nonunion are documented when there is significant displacement (i.e., >2 cm or no cortical contact) and other risk factors such as comminution, z deformity, increasing age, female sex, and smoking [2, 3, 12, 16–18].

In a systematic review of 2144 clavicle fractures, a nonunion rate of 15% with nonoperative management was found [19]. Displacement and comminution were the primary risk factors contributing to nonunion. Operative treatment resulted in a relative risk reduction of 86% for nonunion. It is possible that a displacement of 2 cm noted on X-ray may be underestimating fracture severity. Because of the clavicle's signature S-shape, the dimensions of the bone are often misrepresented on two-dimensional film. A recent three-dimensional clavicle morphometry study investigated the difference between total clavicle length and true clavicle length [5]. Total clavicle length is a straight end-to-end measurement in the frontal plane, while true length is the length of the bone if it were straight (Fig. 2.6). The study found an average of 1.5 cm difference between these two types of measurements. True length of the clavicle is a superior estimation of the bone's length as it takes into account the curvatures in 3-D space, and suggests a longer region of bone overlap not appreciable on X-ray.

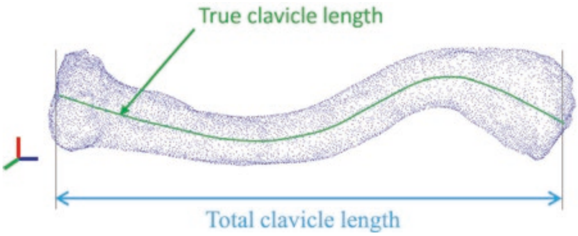

Fig. 2.6 The difference between two types of clavicle length measurement: true length in *green*, total length in *blue*

Operative Versus Nonoperative Management of Midshaft Clavicular Fractures

The first randomized controlled trial (RCT) in 2007 demonstrated earlier healing rates (16 versus 28 weeks) and lower nonunion rates (3% versus 11%) for ORIF compared to nonoperative management [20]. In addition, operative treatment resulted in better DASH scores and fewer symptomatic malunions. However, there was a 12% complication rate with surgical management—mainly symptomatic hardware.

Virtanen in 2012 reported on an RCT of 60 patients with 1 year average follow up [21]. Nonunion rates were 0% for ORIF versus 24% for sling. Complication rates were 7% for ORIF versus 12% for sling, none were major. The patients with nonunions [6] and malunions [2] in the sling group had worse DASH scores.

Robinson in 2013 reported a significantly reduced nonunion rate and better outcome scores after ORIF compared to nonoperative treatment (1% compared to 16%) [16]. When nonunion patients were excluded from analysis however, there were no differences in functional outcome between operative and nonoperative treatment. Improved outcomes resulted from the prevention of nonunion. Due to the cost and implant-related complications, the authors did not support routine primary ORIF for the treatment of displaced midshaft clavicular fractures.

Indications

Open or impending open injuries, neurologic or vascular compromise, unstable or displaced floating shoulder injury, and posteriorly displaced medial clavicular fractures or sternoclavicular injuries constitute absolute indications.

Relative indications for surgical treatment include widely displaced fractures with shortening >2 cm or significant comminution, unacceptable cosmesis, multiply injured trauma patients, predicted functional deficits, and painful nonunion or malunion.

Surgical Techniques

Plate Fixation

Open reduction and internal fixation can be done with a superior or anterior-inferior plate position. Newer plate technology allows for pre-contoured plates that are lower profile and allow locking fixation if necessary [22].

The surgical approach should allow for cosmesis and prevent wound complications. A full-thickness skin and subcutaneous layer should be created down to the platysma, which is then incised longitudinally along the clavicle and then the muscle insertions of the pectoralis major, trapezius, and deltoid on the clavicle are released as required. This will allow for a full thickness fascial layer over the plate at the time of closure.

Superior plate fixation allows the plate to be placed on the tension surface of the bone and requires less muscle origin release. Anterior-inferior plating allows for reduced plate prominence and less plate irritation. In addition, screw length is increased and there is less risk of neurovascular injury during drilling during lateral screw placement [6]. Reconstruction plates are malleable allowing contouring to the patient's anatomy but are weak in comparison to dynamic compression plates. Standalone semi-tubular plates should be avoided.

Anatomically contoured plates fit most of the time and are lower profile which lessens the chance of needed plate removal, but they are more expensive [22]. In cases of comminution, the use of mini-fragment screws can be useful to allow for reduction and lagging of small butterfly fragment and an anatomic reduction. The plate is then placed as a neutralization plate.

The biomechanics on plating position are mixed. Some studies favor superior plating, others anterior plating and finally results may differ in the same study depending on loading conditions [23–25].

Intramedullary Fixation

Intramedullary devices for clavicle fracture fixation may result in shorter operating room time, less narcotic use, fewer complications, and less symptomatic hardware [26]. However, intramedullary devices are biomechanically inferior to plates [27], especially with increasing comminution. Cannulated screws, flexible nails, and clavicle-specific pins for the treatment of these fractures have been reported. The use of small diameter smooth pins is contraindicated. A systematic review comparing plate fixation versus intramedullary devices for displaced clavicle fractures did not show differences in functional outcome or complication rates [26].

Surgical Treatment of Malunion/Nonunion

Malunion and/or nonunion of a clavicle fracture have adverse effects on the functional result; risk factors were discussed. The goal in the treatment of malunions and nonunions of the clavicle is to restore clavicular length and anatomy. This may require an osteotomy as well as possible tricortical interposition graft. Lag screws should be used if possible to allow for compression across the fracture nonunion site.

The clavicular length is evaluated preferably on a computed tomography of both clavicles or at a minimum on anteroposterior and oblique radiographs of both clavicles. If there is greater than 2 cm of shortening, then an osteotomy with interposition bone grafting should be considered to restore the appropriate length.

Plate fixation of clavicle nonunions and malunions provides high union rates and improvement in shoulder function. Plates and nails have been used successfully [12, 28–30]. We favor plates due to higher torsional rigidity.

Biomechanical Considerations for Nailing and Plating

Intramedullary Nailing

Intramedullary nailing of this curved bone deserves some special consideration. A nail can be introduced through a medial entry point, a lateral entry point, and finally through the fracture site. If a nail is introduced through the fracture site, then it must be advanced through the medial or lateral end of the bone to allow reduction of the fracture and then reinsertion to the desired depth.

The unique features of the clavicle, especially its curvature, narrowing offset between clavicle and IM canal, and IM canal eccentricity influence the design of the IM device in both size and shape. The implant must be flexible enough to adapt to the S-shape of the clavicle, thin enough to pass through the narrow middle portion but also strong enough to allow clavicle healing and minimize interfragmentary motion below the nonunion threshold.

The unique curvatures of the IM canal also dictate implant insertion, as they represent the safest trajectory an IM device would take as it is being introduced into the canal (Fig. 2.7) [31]. Due to the clavicle shape the implant will predictably exit the anterior cortex medially and the posterior cortex laterally [31].

Therefore, different types of implant can been utilized [32]:

(a) Titanium nails/K wires/Cannulated screws: These implants are typically introduced through a medial entry site or more commonly through the fracture, out the anterior medial cortex and retrograded into place.
(b) "Locking" nails: Examples are the older Hagie and Rockwood nails and the newer Sonoma nail. These nails are introduced through the fracture, exit out the posterior lateral cortex and then advanced antegrade and engage the medial cortex. The Hagie and Rockwood nail use a similar philosophy of compressing

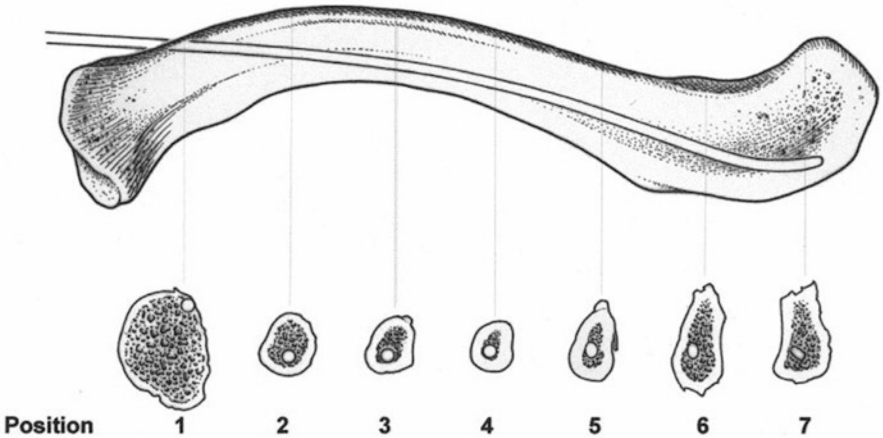

Fig. 2.7 Position of the TEN within the clavicular canal. Contact point and the cortical thickness next to the respective positions become clear. The medial and lateral portions of the bone are the danger zones for nail perforation, while in the middle third a relative narrowing is present. From Andermahr et al.

the fracture using a lateral nut and fixation into the medial end. The Sonoma nail affords true locking screws laterally and the medial fragment is engaged with deployable spikes. The reader is referred to the manufacturer websites for further details on the surgical technique.

Plating

Surgeons have used DCP plates and reconstruction plates, locking and non-locking variations. Due to the biomechanical advantages of locking and the ease of use afforded by pre-contoured plates they are dominating the implant use at this time. It should be noted that pre-contoured plates do not always fit well and hence intraoperative further contouring may be necessary and the surgeon should have the necessary tools available [22]. There is significant debate over superior versus anterior plate position.

Clinical studies support anterior plating as advantageous in terms of secondary operations for removal of hardware [33]. Otherwise, the literature offers mixed results of biomechanical advantage of superior versus the other location [23–25, 34]. Union rates are similar. Since union rates and biomechanical results appear relatively equivalent, we prefer anterior plate position to minimize irritation by hardware and secondary removal of hardware. Three studies suggest that unicortical screws may offer sufficient fixation strength with locking plates [34–36], but it is our preference to use bicortical screws.

Nails Versus Plates

In a systematic review of 2144 clavicle fractures, the nonunion rate was slightly higher for intramedullary nails 1.6% for 364 fractures versus 2.5% for 635 plated fractures (pooled data) [19]. Other comparative studies have shown similar results, i.e., slightly higher rates of nonunion for nailing, but overall very satisfactory results for nailing [26]. Nails have also been used for repair of clavicle malunions [28].

Biomechanical comparison of nailing versus plating demonstrates better stability for plating [28]. The reason that nailing has a higher nonunion rate than plating is perhaps not only device-related but biology-related; the hematoma which typically affords excellent healing after IM nailing of long bones is removed during the process of reduction and introduction of the device for a clavicle fracture. Therefore, in highly comminuted fractures we prefer plating. Nailing is very successful for simpler fracture patterns. One should also consider that most of the intramedullary implants are designed to be removed postoperatively after union; however; this procedure can be typically done with sedation/local anesthetic avoiding general anesthetics.

Conclusion

The clavicle is an important osseous link of the upper extremity to the axial skeleton. Preservation of length and anatomy is important for optimal function of the upper extremity. The most frequent fracture location is in the mid-diaphysis, the isthmus, where the bone is the narrowest. Operative treatment has shown superior results in displaced fractures. Nailing and plating are both acceptable methods of treatment with a different subset of complications and reoperations. This chapter should help the surgeon be more cognizant of the type of implant he/she uses and the biomechanical/clinical considerations.

References

1. Van Tongel A, Piepers I, De Wilde L. The significance of the clavicle on shoulder girdle function. J Shoulder Elb Surg/Am Shoulder Elb Surg [et al]. 2015;24(9):e255–9.
2. Nowak J, Holgersson M, Larsson S. Can we predict long-term sequelae after fractures of the clavicle based on initial findings? A prospective study with nine to ten years of follow-up. J Shoulder Elb Surg/Am Shoulder Elb Surg [et al]. 2004;13(5):479–86.
3. McKee MD, Pedersen EM, Jones C, Stephen DJ, Kreder HJ, Schemitsch EH, et al. Deficits following nonoperative treatment of displaced midshaft clavicular fractures. J Bone Joint Surg Am. 2006;88(1):35–40.
4. Rubright J, Kelleher P, Beardsley C, Paller D, Shackford S, Beynnon B, et al. Long-term clinical outcomes, motion, strength, and function after total claviculectomy. J Shoulder Elb Surg/Am Shoulder Elb Surg [et al]. 2014;23(2):236–44.

5. Aira J. Image-based 3D morphometric analysis of the clavicle intramedullary (IM) canal. Tampa: University of South Florida; 2016.
6. Sinha A, Edwin J, Sreeharsha B, Bhalaik V, Brownson P. A radiological study to define safe zones for drilling during plating of clavicle fractures. J Bone Joint Surg Br. 2011;93(9):1247–52.
7. Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of the shoulder complex during multiplanar humeral elevation. J Bone Joint Surg. 2009;91(2):378–89.
8. Inman VT, deC M Saunders JB, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg. 1944;26(1):1–30.
9. Fukuda K, Craig EV, An KN, Cofield RH, Chao EY. Biomechanical study of the ligamentous system of the acromioclavicular joint. J Bone Joint Surg. 1986;68(3):434–40.
10. Robinson CM. Fractures of the clavicle in the adult. Epidemiology and classification. J Bone Joint Surg Br. 1998;80(3):476–84.
11. Ristevski B, Hall JA, Pearce D, Potter J, Farrugia M, McKee MD. The radiographic quantification of scapular malalignment after malunion of displaced clavicular shaft fractures. J Shoulder Elb Surg/Am Shoulder Elb Surg [et al]. 2013;22(2):240–6.
12. McKee MD, Wild LM, Schemitsch EH. Midshaft malunions of the clavicle. J Bone Joint Surg Am. 2003;85-A(5):790–7.
13. Patel B, Gustafson PA, Jastifer J. The effect of clavicle malunion on shoulder biomechanics; a computational study. Clin Biomech (Bristol, Avon). 2012;27(5):436–42.
14. Hillen RJ, Burger BJ, Pöll RG, van Dijk CN, Veeger DHEJ. The effect of experimental shortening of the clavicle on shoulder kinematics. Clin Biomech (Bristol, Avon). 2012;27(8):777–81.
15. Neer II. CS. Nonunion of the clavicle. J Am Med Assoc. 1960;172:1006–11.
16. Robinson CM, Goudie EB, Murray IR, Jenkins PJ, Ahktar MA, Read EO, et al. Open reduction and plate fixation versus nonoperative treatment for displaced midshaft clavicular fractures: a multicenter, randomized, controlled trial. J Bone Joint Surg. 2013;95(17):1576–84.
17. Hill JM, McGuire MH, Crosby LA. Closed treatment of displaced middle-third fractures of the clavicle gives poor results. J Bone Joint Surg Br. 1997;79(4):537–9.
18. Wick M, Muller EJ, Kollig E, Muhr G. Midshaft fractures of the clavicle with a shortening of more than 2 cm predispose to nonunion. Arch Orthop Trauma Surg. 2001;121(4):207–11.
19. Zlowodzki M, Zelle BA, Cole PA, Jeray K, McKee MD. Treatment of acute midshaft clavicle fractures: systematic review of 2144 fractures: on behalf of the Evidence-Based Orthopaedic Trauma Working Group. J Orthop Trauma. 2005;19(7):504–7.
20. Society COT. Nonoperative treatment compared with plate fixation of displaced midshaft clavicular fractures. A multicenter, randomized clinical trial. J Bone Joint Surg. 2007;89(1):1–10.
21. Virtanen KJ, Remes V, Pajarinen J, Savolainen V, Björkenheim J-M, Paavola M. Sling compared with plate osteosynthesis for treatment of displaced midshaft clavicular fractures: a randomized clinical trial. J Bone Joint Surg. 2012;94(17):1546–53.
22. Huang JI, Toogood P, Chen MR, Wilber JH, Cooperman DR. Clavicular anatomy and the applicability of precontoured plates. J Bone Joint Surg. 2007;89(10):2260–5.
23. Celestre P, Roberston C, Mahar A, Oka R, Meunier M, Schwartz A. Biomechanical evaluation of clavicle fracture plating techniques: does a locking plate provide improved stability? J Orthop Trauma. 2008;22(4):241–7.
24. Partal G, Meyers KN, Sama N, Pagenkopf E, Lewis PB, Goldman A, et al. Superior versus anteroinferior plating of the clavicle revisited: a mechanical study. J Orthop Trauma. 2010;24(7):420–5.
25. Iannotti MR, Crosby LA, Stafford P, Grayson G, Goulet R. Effects of plate location and selection on the stability of midshaft clavicle osteotomies: a biomechanical study. J Shoulder Elb Surg. 2002;11(5):457–62.
26. Houwert RM, Wijdicks F-J, Steins Bisschop C, Verleisdonk E-J, Kruyt M. Plate fixation versus intramedullary fixation for displaced mid-shaft clavicle fractures: a systematic review. Int Orthop. 2012;36(3):579–85.

27. Golish SR, Oliviero JA, Francke EI, Miller MD. A biomechanical study of plate versus intramedullary devices for midshaft clavicle fixation. J Orthop Surg Res. 2008;3:28.
28. Smekal V, Deml C, Kamelger F, Dallapozza C, Krappinger D. Corrective osteotomy in symptomatic midshaft clavicular malunion using elastic stable intramedullary nails. Arch Orthop Trauma Surg. 2010;130(5):681–5.
29. Hillen RJ, Eygendaal D. Corrective osteotomy after malunion of mid shaft fractures of the clavicle. Strategies Trauma Limb Reconstr. 2007;2(2–3):59–61.
30. McKee MD, Wild LM, Schemitsch EH. Midshaft malunions of the clavicle. Surgical technique. J Bone Joint Surg. 2004;86-A(Suppl 1):37–43.
31. Andermahr J, Jubel A, Elsner A, Johann J, Prokop A, Rehm KE, et al. Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. Clin Anat (New York). 2007;20(1): 48–56.
32. Eichinger JK, Balog TP, Grassbaugh JA. Intramedullary fixation of clavicle fractures: anatomy, indications, advantages, and disadvantages. J Am Acad Orthop Surg. 2016;24:455–64.
33. Collinge C, Devinney S, Herscovici D, DiPasquale T, Sanders R. Anterior-inferior plate fixation of middle-third fractures and nonunions of the clavicle. J Orthop Trauma. 2006;20(10):680–6.
34. Croley JS, Morris RP, Amin A, Lindsey RW, Gugala Z. Biomechanical comparison of bicortical, unicortical, and unicortical far-cortex-abutting screw fixations in plated comminuted midshaft clavicle fractures. J Hand Surg Am. 2016;41(6):703–11.
35. Bravman JT, Taylor ML, Baldini T, Vidal AF. Unicortical versus bicortical locked plate fixation in midshaft clavicle fractures. Orthopedics. 2015;38(5):e411–6.
36. Hamman D, Lindsey D, Dragoo J. Biomechanical analysis of bicortical versus unicortical locked plating of mid-clavicular fractures. Arch Orthop Trauma Surg. 2011;131(6):773–8.

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