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The vascularized medial femoral condyle free flap for reconstruction of segmental recalcitrant nonunion of the clavicle

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Background: Recalcitrant clavicular nonunion is a rare but complicated problem of clavicular fracture fixation. Nonunion is most often treated with clavicular shortening or in extreme cases vascularized bone grafting. Herein we describe our experience using the vascularized medial femoral condyle (MFC) free flap for the reconstruction of segmental defects in cases of recalcitrant clavicular nonunion.
Methods: A retrospective chart review was conducted of patients with symptomatic recalcitrant nonunion of the clavicle who underwent reconstruction with the vascularized MFC free flap from June 2003 to January 2018. Patients' demographics, time to union, and postoperative complications were collected.
Results: A total of 7 patients (6 women; 39.8 ± 9.01 years old) underwent clavicular reconstruction after an average of 3.7 ± 1.3 previous surgical procedures. Average preoperative visual analog scale score for pain was 4.1. The graft size ranged from 2 to 5 cm in length with approximately 1 cm in width and depth. The average time of total nonunion was 66 ± 48.2 months before surgery. All flaps survived and all clavicles healed with an average time to radiographic union of 15 ± 6.7 months. Patients regained full shoulder motion, and average postoperative visual analog scale score was 1.6 ± 1.8. All patients returned to their preoperative employment status. Donor site morbidity from the knee was minimal.
Conclusion: The MFC free flap is a good option for recalcitrant bone nonunion of the clavicle where larger vascularized flaps are not warranted. It is effective and offers minimal donor site morbidity.
Level of evidence: Level IV; Case Series; Treatment Study

Keywords: Clavicle; clavicular nonunion; medial femoral condyle; recalcitrant nonunion; segmental defect; vascularized bone graft

The rate of clavicular fracture is estimated to be 5.8 fractures per 10,000 persons in the United States.[22] Although most of these fractures heal without major complications, nonunion rates have been reported to be between 0.1% and 0.8%.[29,39] However, certain conditions, such as

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radiotherapy, initial fracture displacement, comminution, and advanced age, can lead to healing problems and subsequent risk for clavicle nonunion.[13,30,40]

Symptomatic nonunion can lead to significant morbidity with gross deformity, chronic pain, and functional compromise.[9,46] Traditional methods for achieving union after initial failed treatment of these fractures involve the use of internal fixation (plating, lag screws, intramedullary nails) and bone grafting, with reported good union rates of 70%-95%.[14,16,48] In rare cases, total resection of the clavicle has been performed to palliate the problem of nonunion or unrepairable fractures.[25,27,46,49] Loss of clavicular continuity can lead to malposition of the scapula with movement and result in long-term functional impairments of the shoulder.[32,41] This can translate into disabling myalgia and shoulder instability with resultant decreased range of motion, weakness, and, in some cases, irritation of the brachial plexus.[17,25,41] In such instances, these morbidities can persist even after total claviculectomy. Currently, there are several contradicting reports in the literature; some described improved outcomes after total claviculectomy, whereas others described corresponding upper limb weakness and persistence of intractable pain.[9,27,34,46,49]

Even though recalcitrant nonunion is rare after the traditional approach of internal fixation with nonvascularized bone grafts, the use of vascularized bone grafts has become the standard of care in the event of recalcitrant nonunion.[15,45] With the preservation of blood supply and osteocytes in the graft, the process of bone remodeling is more instant, with high osteogenic capabilities.[24,43] In addition, vascularized bone grafts are believed to induce angiogenesis, which ultimately facilitates healing and clears lingering infection from the area.[7] Several vascularized bone grafts have been described and can be harvested from different locations in the body, including fibula, iliac crest, rib, radius, and medial femoral condyle (MFC).

There are case reports in the literature describing the successful use of MFC flap for clavicle reconstruction as a vascularized periosteal wrap, but none focus on intercalated defects of >3 cm.[4,13] Herein, we review our experience of clavicle recalcitrant nonunion reconstruction using vascularized MFC free flap as a segmental (≤5-cm structural) graft, looking specifically at donor site morbidity, flap complications, and clinical outcomes.

Methods

A retrospective chart review was performed. All patients who underwent vascularized MFC free flap for clavicle reconstruction from June 2003 to January 2018 were included through an institutional research search engine. All flaps were done for symptomatic recalcitrant bone nonunions and performed by the senior author.

Patients' demographics, presenting symptoms, cause of injury, treatment history, location of nonunion, flap size, time of nonunion, time to heal after flap reconstruction, donor and recipient site complications, and outcomes at the latest follow-up were documented by the second senior author, who was the operating orthopedic surgeon. Total nonunion time was defined as time from injury to imaging. A plain film radiograph was taken at each follow-up and interpreted by a radiologist after MFC flap to confirm bone union. From MFC flap to union time was defined as the time from flap procedure to imaging-confirmed bone union by bone bridging at 3 cortices.

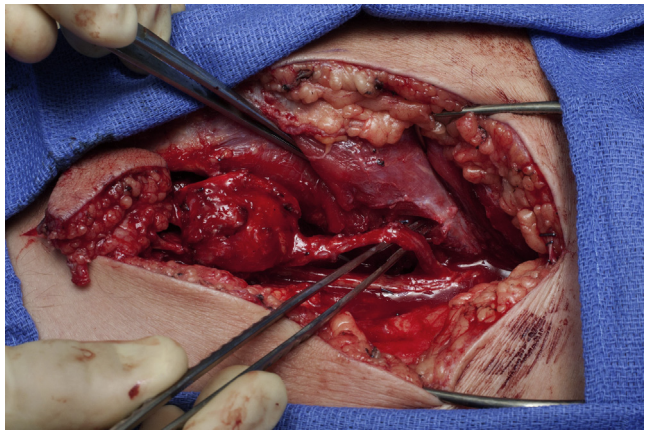

Figure 1 Intraoperative view of a vascularized medial femoral condyle free flap with a skin island and its vascular pedicle.

Surgical technique

Non-contrast-enhanced computed tomography with 3-dimensional reconstruction was used to assess the nonunion site and to estimate the extent of débridement required. The intact contralateral clavicle was also measured to estimate the normal physiologic clavicle length for each patient.

The flap harvesting technique was previously described by Sakai et al[42] and Iorio et al.[19] Briefly, the patient is placed in a supine position such that the leg is flexed at the knee and the hip externally rotated. The skin perforators for the MFC flap are identified in the medial distal third of the thigh with a hand-held Doppler probe (Summit LifeDop L350R; Wallach Surgical Devices, Trumbull, CT, USA). This is usually identified just proximal to the condyle and posterior to the midline. The thoracoacromial artery and its concomitant vein are the preferred recipient vessels. However, when the vessels are not satisfactory for anastomosis, the transverse cervical artery, external jugular vein, subclavian vein, and branches of cephalic veins are used as alternatives. For MFC flap harvest, a midaxial incision is made directly over the MFC, extending from midthigh to the level of the patella. Dissection is carried down to vastus medialis fascia, which is incised, and the muscle is retracted anteriorly. The descending genicular vessels are identified as they emerge from the adductor magnus before their entry into Hunter canal. The branches are dissected until they are seen entering the periosteum. The saphenous branch is followed to its subcutaneous level and a skin island can be harvested with the flap (Fig. 1). The superomedial genicular branch is identified at the metaphyseal level and can be used if the descending branch is not of adequate size. The required size of the graft is outlined on the supracondylar region and elevated

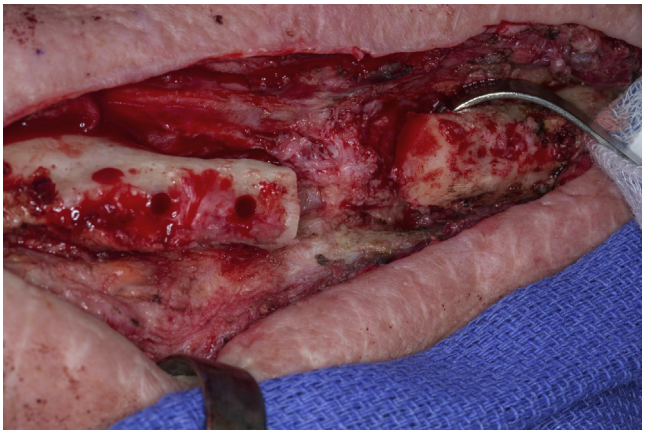

Figure 2 Intraoperative view of a clavicular defect after thorough surgical débridement.

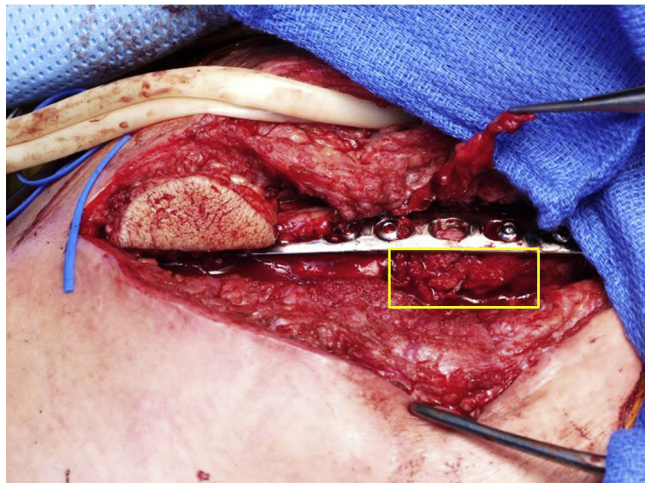

Figure 3 Inset of vascularized medial femoral condyle flap. The *yellow box* indicates location of bone inset.

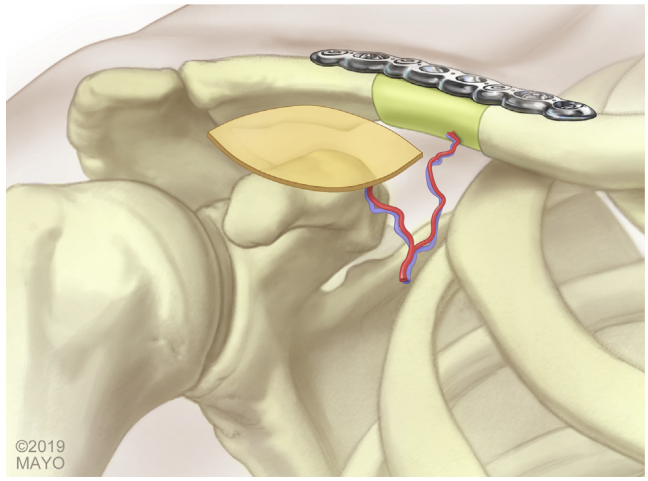

Figure 4 Medial femoral condyle flap with a skin paddle for segmental reconstruction of clavicle. (By permission of Mayo Foundation for Medical Education and Research. All rights reserved.)

with an osteotome and sagittal saw. The articular surface and medial collateral ligament of the knee are protected during harvest. The dissection usually results in a rectangular bone flap of approximately 1 cm in width, 1 cm in depth, and 2 to 5 cm in length that includes the periosteum and a skin monitoring flap. The donor site is closed primarily.

After the nonunion site is fully débrided (Fig. 2), the graft is brought to the recipient site and trimmed to fit the clavicular defect. Fixation is done with a dynamic compression plate in all cases. The graft is placed between the 2 ends of the clavicle defect with a clamp as the plate is positioned (Figs. 3 and 4). With use of a compression technique, the graft is first fixed in position by tightening of the compression screws. A single locking screw is often then placed into the graft for final fixation of the graft. Once adequate fixation is obtained, microvascular anastomosis is performed. Postoperatively, the flap is monitored through examination of the skin paddle or an external (Summit LifeDop L350R) or implantable Doppler (Cook-Swartz Doppler Probe; Cook Medical, Bjaeverskov, Denmark) probe. Each patient wore a shoulder immobilizer for 6-8 weeks, after which passive range of motion was initiated. In addition, each patient was allowed to bear weight as tolerated in the lower extremity with a supplemental knee brace for 2 weeks.

Statistical analysis

Values obtained from preoperative and postoperative visual analog scale (VAS) were compared with a 2-sample *t*-test according to Kim.[23] A significance level of $\alpha < .05$ was used, and all results were presented as mean $\pm$ standard deviation (SD).

Results

There were 7 cases of clavicular reconstruction with vascularized MFC free flap for symptomatic recalcitrant clavicular nonunion in the defined study period. There were 1 male and 6 female patients with an average age of 39.8 years (range, 23-51 years [SD, 9.01]). Two patients were former smokers, 3 patients were obese (BMI >30 kg/m^2), 3 patients had hypertension, 1 patient previously had breast cancer and had radiotherapy to the chest and clavicle, and 1 patient had anemia. There were no diabetic patients. The average body mass index was 30.6 kg/m^2 (range, 26.7-37.8 kg/m^2 [SD, 4.7]; Supplementary Table S1). Three patients had a history of osteomyelitis at the nonunion site.

Patients' occupations included 1 dog trainer, 1 horseback riding instructor, 1 retired laboratory technician, 2 nursing students, 1 nurse, and 1 unemployed. All patients were still able to work despite their shoulder complaints. In all cases, the cause of the clavicle fracture was trauma (fall from height, 5; motor vehicle accident, 1; physical abuse, 1). The location of the fracture was the midshaft of the clavicle (Fig. 5). One patient had inferior displacement of the lateral segment. Two patients had fracture diastasis after

Figure 5 A case of recalcitrant clavicular nonunion with 5 previous surgical repairs complicated by infection and broken hardware.

the initial operation (Supplementary Table S1). Two cases were initially treated at our institution, whereas the other 5 cases were initially treated at outside institutions and came to our institution for reconstruction with the MFC flap. Two patients were initially treated conservatively; 1 patient received a figure-of-8 brace, and 1 patient received a sling. All the other patients were treated with open reduction and internal fixation with plates. After failure of the initial management, which was manifested as symptomatic nonunion of the clavicle, patients were treated with different plating systems and different nonvascularized bone grafts including allograft bone and iliac crest bone graft at outside institutions.

Before reconstruction with a vascularized MFC flap, all patients complained of chronic pain over the clavicle that interfered with daily activities, and 1 patient had hardware exposure. Preoperatively, 3 of 7 patients had infection of the surgical site. One patient underwent débridement and hardware removal at our institution; the other 2 patients (including 1 case of osteomyelitis) had the infection treated at an outside institution before coming to us. After the initial surgical failure, 2 patients required the use of bone stimulator, and 1 of those patients received platelet-derived growth factor from the patient's own blood. The number of surgical procedures before reconstruction with MFC flap ranged from 3 to 6, with an average of 3.7 (SD, 1.3) operations. One patient required the placement of vancomycin beads in the nonunion site (Supplementary Table S2).

Two patients had full range of motion despite clavicular nonunion, whereas the others had different degrees of reduced range of motion (Supplementary Table S1). Average preoperative VAS score before MFC flap reconstruction was 4.1 (SD, 1.6). All patients were still able to work despite symptoms of clavicular nonunion.

The MFC flap size ranged from 2 to 5 cm in length and 1 cm in width and depth. One flap included a skin paddle measuring 3 × 3 cm. The descending geniculate artery and its venae comitantes were used in 5 cases as the flap donor vessels; the superomedial genicular vessels were used in the remaining 2 cases. For recipient artery, 2 flaps were anastomosed to the transverse cervical artery; the 5 remaining flaps were anastomosed to the thoracoacromial artery. For venous outflow of the flap, 2 flaps were anastomosed to the external jugular vein, 1 flap to the venae comitantes of thoracoacromial artery, 1 flap to the subclavian vein, and 3 flaps to branches of cephalic vein (Supplementary Table S3).

There were no cases of flap loss, and all nonunion sites were able to achieve healing and symptomatic resolution after vascularized MFC flap reconstruction (Fig. 6) at the latest follow-up (mean, 15 months [SD, 6.7 months]). There was 1 donor site complication of a neuroma at the medial geniculate nerve that was treated successfully with excision 9 months after the MFC flap reconstruction. The average time of total nonunion before vascularized bone grafting was 66 months (range, 13-168 months [SD, 48.2]) from the time of fracture to healing. After reconstruction with the MFC free flap, the mean time to radiologic report of bone union was 15 months (range, 5-24 months [SD, 6.7]; Supplementary Table S3). Average postoperative VAS score was 1.6 (SD, 1.8), which was a significant improvement ($P = .001$) from preoperative values. All patients returned to their preoperative employment status.

Discussion

Here we have presented the first reported series of segmental reconstruction of the clavicle using an MFC vascularized graft. The flap was successful in all patients despite multiple previous surgical procedures. Patients had identifiable risk factors for nonunion, including previous radiotherapy, initial fracture displacement, comminuted fracture, and osteomyelitis.[13,30,40] Union was achieved despite reconstruction of defects >2 cm in length.

Several vascularized flaps have been described for clavicle reconstruction. In 1990, Devaraj et al[10] reported the first case of total clavicle reconstruction after resection of a malignant tumor in an 11-year-old using a pedicle composite rib flap with latissimus dorsi and serratus

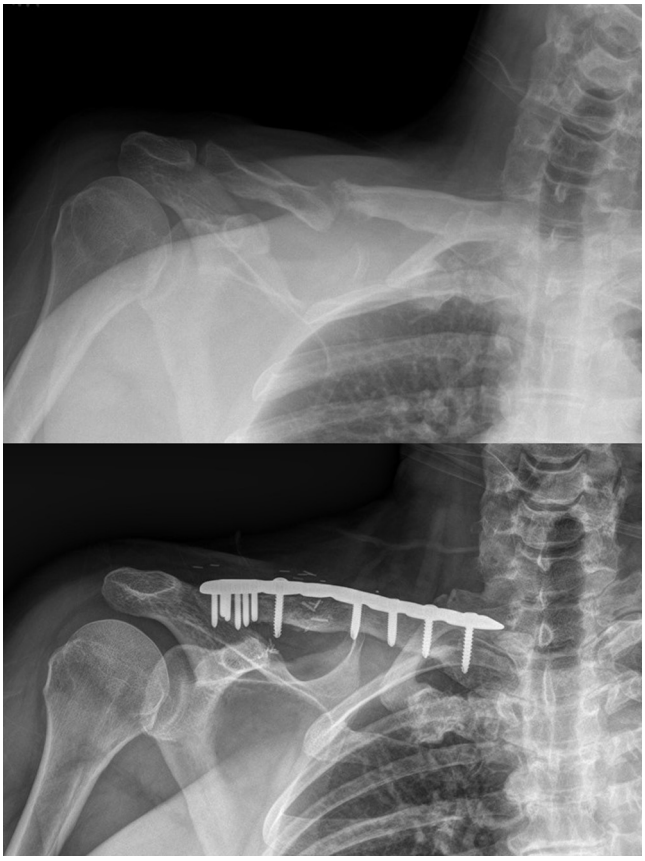

Figure 6 A case of achieving bone union after medial femoral condyle reconstruction. Preoperative radiograph (*top*). Postoperative radiograph at 24 months (*bottom*).

anterior muscles. Adolfsson et al[2] reported 3 cases of disabling symptomatic nonunion after traumatic fracture and resection for osteoarthritis. Whereas 2 of the cases were treated with supportive vest with minimal improvement, the case treated with pedicle composite rib/latissimus dorsi flap had achieved pain relief and improved range of motion and increased strength.[17] Other options described in the literature are free rib graft, iliac crest flap, and split radial bone.[34] However, currently, 2 widely accepted flaps for bone defect and hostile wound beds are the MFC and fibula free flaps.[11]

In 2000, Momberger et al[36] reported the first series of vascularized fibula graft for reconstruction of clavicular nonunion. These were done in 3 trauma cases with defect size ranging from 3 to 8 cm. Other small series reported the successful use of this flap for similar size defects.[12,26] The largest series was reported by Krishnan et al,[25] who treated 8 cases of brachial plexus compression due to clavicular nonunion and pseudarthrosis. Abarca et al[1] reviewed the clinical indications for the use of this flap: clavicular reconstruction after tumor resection with functional loss, reconstruction after infection, and multiple failed internal fixation procedures with segmental loss of >5 cm. For smaller defects, a large vascularized bone flap, such as fibula and iliac crest, may be unnecessary, and the associated long-term donor site morbidity is not justified.[28,33] In those cases, MFC flap is a more suitable choice because of its small size, which results in minimal donor site morbidity.[4]

The use of MFC corticoperiosteal flap for treatment of fracture nonunion was first reported by Sakai et al[42] in 1991. They described the use of this flap in 6 cases of nonunion after failed surgical treatment of fractures of the ulna, humerus, and metacarpal bone. Bone union was achieved in all cases in an average time of 2.3 months. There were no complications, and only one case of mild numbness and pain at the donor site was reported.

Fuchs et al[13] reported their experience with wrapping a thin periosteal flap around the nonunion site. Healing was confirmed in all cases by computed tomography between 3 and 7 months. They described a remarkable improvement of upper extremity function at final follow-up with no reported complications. Choudry et al[7] described the successful use of this flap for recalcitrant, long-standing nonunions, including 2 cases of clavicular nonunion after traumatic fracture complicated by osteomyelitis. Healing was achieved in 2-5 months.[7]

Historically, restoration of segmental defects of the clavicle has required reconstruction with a free fibular graft.[36] This graft has a known donor site morbidity of pain with ambulation, ankle weakness, and great toe weakness or contracture, and it sacrifices a major blood vessel to the lower leg.[3,44] In comparison, the MFC free flap has also previously been reported to reconstruct a segmental defect of the mandible.[31] The MFC flap has the advantage of not having to sacrifice any major vessels of the leg and has been shown to produce minimal donor site morbidity.[35,47] The most commonly reported donor site complication is paresthesia along the distribution of the saphenous nerve.[6,38] Other less frequently encountered complications are reduced knee range of motion and supracondylar fracture.[7,8,47] Patients can usually start ambulating the day after surgery.[19] The flap is easy to dissect and can be harvested up to 5 cm, depending on the size of the defect.[4,7] In addition, the pliable periosteum can be wrapped around tubular bones to provide stabilization and to form a protective environment for bone remodeling.[7,21] The flap has been shown to be extremely effective in healing infected nonunions, but no study has examined its ability to reconstruct segmental defects within the clavicle.

The MFC flap has a consistent anatomy with few variants.[13,20] Its vascular pedicle is usually long and with large-caliber vessels, which can reach the recipient vessels without the need for a vein graft.[4] A study in 2010 has examined in depth the arterial anatomy of the medial femoral condyle based on 19 fresh cadavers; it was found that the descending genicular artery was present in 89% of the specimens, whereas the superomedial genicular artery was present all the time.[50] In addition, the group also reported the average arterial branching from the femoral artery to the articular surface to be 13.7 cm (descending

genicular artery) and 5.3 cm (superomedial genicular artery).[50] Regarding intraosseous vascular supply of the MFC, the group also noted that there was an average of 30 vessels perforating into the bone with an average depth of 13 mm. Although the distribution of perforating vessels was variable, the highest density was noted to be in the distal posterior area of the MFC.[50]

In terms of flap harvesting, besides being harvested as a segmental block with cancellous bone to fill in small defects, the MFC can be harvested as a flexible, thin, and pliable graft. Therefore, it is able to conform well to the recipient site or can be effectively wrapped around nonunion sites on tubular bones with minimal excess bulk.[13,20] Another advantage of the MFC flap is that a large skin paddle can be included with the bone graft. This allows simultaneous coverage of the recipient site soft tissue defect. The skin paddle is based on the saphenous artery branch of the descending genicular artery pedicle. A study in 12 cadaveric legs has demonstrated the average area of saphenous artery branch perfusion to be 361 cm^2.[18] Alternatively, a cutaneous branch of the descending genicular artery at the condyle level can be used to support a smaller skin flap of approximately 70 cm^2.[18]

More recently, besides using vascularized bone grafts for the treatment of recalcitrant clavicular nonunion, Bastian[5] reported the use of dual locking plates in combination with iliac crest autograft, bone marrow aspirate concentrate, and bone stimulator. They reported satisfactory clinical results at 9 months with confirmation of fracture healing and filling of previous screw lucencies on computed tomography images in a 33-year-old woman who had 2 previous treatment failures. No complication was described in this case report. In another study, Morison et al[37] conducted a retrospective outcome study for the use of human recombinant bone morphogenic protein 7 in recalcitrant long bone nonunions of the upper extremity, including 24 clavicle cases. In their study, 2 patients had persistent nonunion, another 2 patients developed fibrous union, and 1 patient had early hardware failure and underwent revision open reduction and internal fixation.

A weakness of this study is the small number of patients (n = 7) included. Only 7 cases were collected during a period of 15 years because of the rare occurrence of clavicle nonunion (0.1%-0.8%).[29,39] Despite this weakness, this study shows that the MFC flap can be used to treat segmental defects (up to 5 cm) of the clavicle with little donor site morbidity, restoration of function, and improvement in pain.

Conclusion

The MFC can provide a segmental structural vascularized bone graft for flap reconstruction that is effective in achieving bone union in recalcitrant nonunion of the clavicle when conventional bone graft techniques have failed. The surgical procedure is well tolerated with minimal donor site morbidity.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jse.2019.04.044.

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