CAUSE

The exact cause of OCD remains unclear. As mentioned above, capitellar OCD most frequently occurs in teenage baseball players. Such epidemiologic evidence lends credence to the roles of microtrauma and overuse in the initiation and progression of this disease. During the acceleration phase of throwing, the elbow is stressed in a valgus direction and this condition significantly loads the capitellum in compression and shear. This can ultimately result in microfracture and disturbance of circulation on the subchondral bone. On the basis of the radiological analysis, Takahara *et al.*[18••] suggested that repetitive microtrauma to the lesions disturbed the union of the newly formed bone during the repair process. The failure of osseous repair leads to bony resorption and separation, with the creation of osteochondral loose bodies. Another causative factor is considered to be a tenuous blood supply to the capitellum due to the low number of feeding vessels. Indeed, osteonecrosis of the subchondral bone is observed in the histopathology of capitellar OCD lesions. On the contrary, inflammatory cell infiltration is absent or minimal and does not contribute to this disease.[19]

DIAGNOSTIC EVALUATION

The diagnosis of capitellar OCD is based on the clinical presentation and radiographic findings.

Clinical Presentation

Capitellar OCD mainly occurs in teenage male athletes. The dominant arm is almost always involved. Takahara *et al.*[18••] reported that bilateral involvement is found in only one of 107 patients and stated that the cause of this bilateral case is constitutional.

The most common subjective symptom is elbow pain with sport activities. The sport related to the onset of the symptoms is usually baseball, gymnastics, weight lifting, and racquet sports. Usually, this symptom is relieved by rest. Although pain is often localized over the lateral aspect of the elbow joint, it may be poorly characterized.

Physical examination may reveal tenderness to palpation, laterally or posteriorly, over the radiocapitellar joint. Range of elbow motion (elbow ROM) is usually limited, particularly extension. In terms of elbow ROM, Takahara *et al.*[18••] have stated that a restriction of the ROM of at least 20° suggests the existence of an unstable fragment. Clicking or locking also indicates fragment instability or loose bodies. The active radiocapitellar compression test as a provocative test is useful to confirm the diagnosis.

It must be noted that patients with capitellar OCD do not always complain of the symptoms mentioned above. Clinicians should ask patients about the symptoms that occur during sport activities. Moreover, baseball players develop a variety of elbow injuries, such as medial epicondylar stress lesions (little league elbow). Therefore, complicated lesions related to the symptoms should not be overlooked.

Radiological evaluation

Plain radiographs are the initial diagnostic test of choice. In addition to standard radiographs, including anteroposterior and lateral views, a tangential with the elbow in 45° of flexion is useful for detecting OCD lesions. The radiographic findings are classified into following three groups: grade I, localized flattening or radiolucency; grade II, a nondisplaced fragment; and grade III, a displaced or detached fragment.[18••] Computed tomography (CT) is useful in identifying the presence and location of loose bodies. With a recent development of imaging technology, MRI has become the most important diagnostic tool for cartilaginous lesions. This diagnostic tool can evaluate the pathological conditions of articular cartilage and subchondral bone, as well as the existence of loose bodies. Several studies in the past few years have demonstrated the usefulness of MRI in diagnosing capitellar OCD and determining the disease stage or classification.[20,21]

Arthroscopy

Under arthroscopic evaluation, cartilaginous lesions can be directly visualized and palpated to evaluate the conditions of lesions, including color, softness, integrity, and stability. Therefore, arthroscopy is considered to be the final diagnostic tool for various types of cartilaginous lesions. Over the past several years, elbow arthroscopy has developed and been applied to the evaluation of capitellar OCD lesions.[22–28]

TREATMENT

Treatment of capitellar OCD is still controversial. In terms of treatment for cartilaginous lesions, several procedures for resurfacing cartilage defects with hyaline cartilage have been developed recently. This development has altered the strategy of treatment for capitellar OCD over the past few years.

Nonoperative Treatment

Capitellar OCD lesions can be classified as stable or unstable. Conservative treatments lead to favorable results when the lesion is stable. Therefore, reliable preoperative criteria for stable lesions are needed to achieve successful outcomes by conservative treatments. Recent studies have shown the effectiveness of MRI for evaluating capitellar OCD lesions to determine the best choice of treatment.[20,21] The grading system of Yamamoto *et al.*[17] was demonstrated to have a correlation with arthroscopic findings. This system classifies MRI findings into five groups as follows: grade 0, normal; grade 1, intact cartilage with signal changes; grade 2, a high-signal breach of the cartilage; grade 3, a thin, high-signal rim extending behind the osteochondral fragment, indicating synovial fluid around the fragment; grade 4, mixed-signal or low-signal loose body, either in the center of the lesion or free within the joint. Lesions with grade 1 or 2 finding are assessed as stable. Yamamoto *et al.*[17] advocated a conservative treatment for such lesions. On the contrary, on the basis of the analysis of 107 patients, Takahara *et al.*[18••] emphasized that stable lesions that healed with conservative treatment were determined by not only radiological grading but also clinical findings. A patient with a stable OCD lesion has all of the following findings at the time of initial presentation: an immature capitellum with an open growth plate, flattening or radiolucency of the subchondral bone (radiographic stable lesion), and almost normal elbow motion. According to this categorization, only nine of 107 patients (8%) had a stable lesion. They stated that the stable lesions determined by the criteria can heal almost completely with conservative treatment. The authors agree with this categorization system for determining stable lesions. In addition, stable lesions responding to conservative treatment may be less than we have expected.

Surgical Treatment

A recent topic related to surgical treatment for capitellar OCD is the application of autologous osteochondral grafts. Since the first report by Nakagawa *et al.*,[29] several clinical studies have demonstrated the surgical efficacy of this procedure against capitellar OCD.[12••,13,15–17] Although each author has performed autologous osteochondral grafts for unstable lesions, there are detailed differences in the surgical techniques used among the authors. Iwasaki *et al.*[13] transplanted two to five small cylindrical grafts (2.7–6.0 mm in diameter) to osteochondral defects in the capitellum (Figure 1). This technique is referred as a mosaicplasty. On the contrary, Ansah *et al.*[12••] used a relatively large-sized osteochondral graft to cover a defect with an average of 9.7 mm diameter. Yamamoto *et al.*[17] transferred osteochondral grafts for reattachment of the lesion as well as osteochondral resurfacing. For large unstable lesions, Takahara *et al.*[18••] concluded that fragment fixation or osteochondral grafts led to better results than simple excision. Regarding fragment fixation, a recent study showed that the histological features of OCD lesions resemble osteoarthritis, and suggested that the cartilage had suffered damage over the long term.[19] Consequently, osteochondral grafts may provide better outcomes by resurfacing the OCD lesions with normal hyaline cartilage, compared with fragment fixation. A considerable disadvantage of autologous osteochondral grafts is the possible adverse effects on the donor sites. In the standard technique of osteochondral mosaicplasty, small cylindrical osteochondral grafts for cartilaginous lesions are harvested from a less weight-bearing area of the knee joint, including the periphery of the lateral femur at the patellofemoral joint and the femoral intercondylar notch. So far study of the effects on knee function following osteochondral graft harvests has been superficial. On the contrary, Iwasaki *et al.*[30•] have shown that 10 of 11 patients achieved a maximum clinical and functional score of the donor knee after this procedure. Additionally, they have reported that all 11 patients were able to return to their previous sport activities without any donor site disturbances. These results indicate no unfavorable effect of graft harvest on the donor knee in young athletes having capitellar OCD treated with osteochondral mosaicplasty.

Another recent topic is the application of arthroscopic surgery to capitellar OCD. A standard surgical approach currently used involves arthroscopic evaluation and debridement with drilling or microfracture of OCD lesions. Bojanić *et al.*[22] showed excellent short-term results in adolescent gymnasts with capitellar OCD treated with a combination of arthroscopy and the microfracture technique. A prospective cohort study of 15 patients demonstrated that arthroscopic debridement for capitellar OCD lesions achieved good results, with pain relief during activities of daily living and sport.[26] The function of the elbow, as assessed by the modified Andrews elbow scoring system, improved from poor to excellent. On the contrary, Brownlow *et al.*[23] reported that a disappointing high number of patients (38%) had recurrent symptoms of locking and catching after arthroscopic debridement and loose body retrieval. In the review article, Steinmann[28] stated that early arthroscopic treatment of young patients with debridement of loose fragments and loose edges of cartilage may be effective. However, it has not been shown that arthroscopic drilling or microfracture for capitellar OCD lesions results in any better prognosis for the patient. The outcome studies in the past few years have emphasized that arthroscopic treatments for capitellar OCD lesions should be improved to significantly overcome the results of open surgeries.[22,23,26] As new technology and techniques develop, the indications for arthroscopic treatment of capitellar OCD will expand and its clinical outcomes will improve.

CONCLUSION

During the past few years, the surgical strategy for capitellar OCD has tended to shift from marrow-stimulating techniques

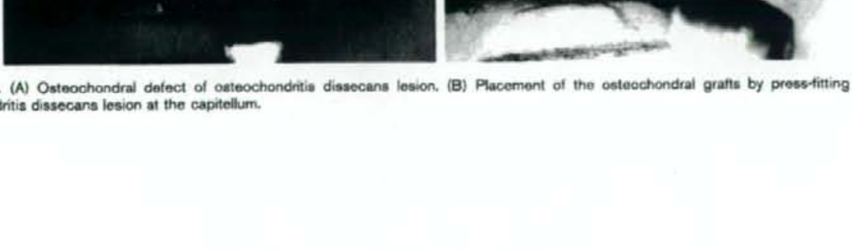

FIGURE 1. (A) Osteochondral defect of osteochondritis dissecans lesion. (B) Placement of the osteochondral grafts by press-fitting flush to the osteochondritis dissecans lesion at the capitellum.

to osteochondral grafts as a cartilage-resurfacing technique. In addition, arthroscopic surgery as a minimally invasive procedure for OCD lesions has been expanded as a treatment for other elbow disorders. The prevalence of capitellar OCD is high among teenage athletes. Therefore, the goal of treatment for this disease is to return patients to their previous level of sport activities and to regenerate long-lasting hyaline cartilage tissue to replace cartilaginous lesions. To achieve this treatment goal, a combination of cartilage-resurfacing techniques and elbow arthroscopy – arthroscopic cartilage-resurfacing procedure – may be an ideal treatment for capitellar OCD.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Peterson RK, Savoice FH III, Field LD. Osteochondritis dissecans of the elbow. *Instr Course Lect.* 1999; 48:393–398.
2. Bauer M, Jonsson K, Josefsson PO, Lindén B. Osteochondritis dissecans of the elbow: a long-term follow-up study. *Clin Orthop Relat Res.* 1992; 284:156–160.
3. Kiyoshige Y, Takagi M, Yuasa K, Hamasaki M. Closed-wedge osteotomy for osteochondritis dissecans of the capitellum. A 7- to 12-year follow-up. *Am J Sports Med.* 2000; 28:534–537.
4. McManama GB Jr, Micheli LJ, Berry MV, Sohn RS. The surgical treatment of osteochondritis of the capitellum. *Am J Sports Med.* 1985; 13:11–21.
5. Takahara M, Ogino T, Sasaki I, *et al.* Long term outcome of osteochondritis dissecans of the humeral capitellum. *Clin Orthop Relat Res.* 1999; 363:108–115.
6. Hangody L, Ráthonyi GK, Duska Z, *et al.* Autologous osteochondral mosaicplasty. Surgical technique. *J Bone Joint Surg.* 2004; 86A: 65–72.
7. Hangody L, Füles P. Autologous osteochondral mosaicplasty for the treatment of full-thickness defects of weight-bearing joints. Ten years of experimental and clinical experience. *J Bone Joint Surg.* 2003; 85A:25–32.
8. Hangody L, Feczkó P, Bartha L, *et al.* Mosaicplasty for the treatment of articular defects of the knee and ankle. *Clin Orthop Relat Res.* 2001; 391:328–336.
9. Knutsen G, Drogset JO, Engebretsen L, *et al.* A randomized trial comparing autologous chondrocyte implantation with microfracture. Findings at five years. *J Bone Joint Surg.* 2007; 89A:2105–2112.
10. Steinwachs M, Kreuz PC. Autologous chondrocyte implantation in chondral defects of knee with a type I/III collagen membrane: a prospective study with a 3-year follow-up. *Am J Sports Med.* 2007; 35:1261–1268.
11. Mandellbaum B, Browne JF, Fu F, *et al.* Treatment outcomes of autologous chondrocyte implantation for full-thickness articular cartilage defects of the trochlea. *Am J Sports Med.* 2007; 35:915–921.
12. •• Ansah P, Vogt S, Ueblacker P, *et al.* Osteochondral transplantation to treat osteochondral lesions in the elbow. *J Bone Joint Surg.* 2007; 89A:2188–2194.

The authors used a relatively large-sized osteochondral graft to cover the defect with an average of 9.7 mm diameter. The mid-term follow-up suggests that the described technique provides overall good to excellent results for unstable OCD lesions of the capitellum.

13. Iwasaki N, Kato H, Ishikawa J, *et al.* Autologous osteochondral mosaicplasty for capitellar osteochondritis dissecans in teenaged patients. *Am J Sports Med.* 2006; 34:1233–1239.
14. Sato M, Ochi M, Uchio Y, *et al.* Transplantation of tissue-engineered cartilage for excessive osteochondritis of the elbow. *J Shoulder Elbow Surg.* 2004; 13:221–225.
15. Shimada K, Yoshida T, Nakata K, *et al.* Reconstruction with an osteochondral autograft for advanced osteochondritis dissecans of the elbow. *Clin Orthop Relat Res.* 2005; 453:140–147.
16. Tsuda E, Ishibashi Y, Sato H, *et al.* Osteochondral autograft transplantation for osteochondritis dissecans of the capitellum in nonthrowing athletes. *Arthroscopy.* 2005; 21:1270.e1–1270.e4.
17. Yamamoto Y, Ishibashi Y, Tsuda E, *et al.* Osteochondral autograft transplantation for osteochondritis dissecans of the elbow in juvenile baseball players: minimum 2-year follow-up. *Am J Sports Med.* 2006; 34:714–720.
18. •• Takahara M, Miura N, Sasaki J, *et al.* Classification, treatment, and outcome of osteochondritis dissecans of the humeral capitellum. *J Bone Joint Surg.* 2007; 89A:1205–1214.

The results of this study were based on the data of large patient population. A significance of this study is the determination of criteria for deciding the adequate treatment for capitellar OCD. Stable lesions responding to nonoperative treatment have all of the following findings: an open capitellar growth plate, localized flattening or radiolucency of the subchondral bone, and good elbow motion.

19. Kusumi T, Ishibashi Y, Tsuda E, *et al.* Osteochondritis dissecans of the elbow: histopathological assessment of the articular cartilage and subchondral bone with emphasis on the damage and repair. *Pathol Int.* 2006; 56:604–612.
20. Kijowski R, De Smet AA. MRI findings of osteochondritis dissecans of the capitellum with surgical correlation. *Am J Roentgenol.* 2005; 185:1453–1459.
21. Link TM, Mischung J, Wörtler K, *et al.* Normal and pathological MR findings in osteochondral autografts with longitudinal follow-up. *Eur Radiol.* 2006; 16:88–96.
22. Bojanić I, Ivković A, Borić I. Arthroscopy and microfracture technique in the treatment of osteochondritis dissecans of the humeral capitellum: report of three adolescent gymnasts. *Knee Surg Sports Traumatol Arthrosc.* 2006; 14:491–496.
23. Brownlow HC, O'Connor-Read LM, Perko M. Arthroscopic treatment of osteochondritis dissecans of the capitellum. *Knee Surg Sports Traumatol Arthrosc.* 2006; 14:198–202.
24. Davis JT, Idjadi JA, Siskosky MJ, ElAttrache NS. Dual direct lateral portals for treatment of osteochondritis dissecans of the capitellum: an anatomic study. *Arthroscopy.* 2007; 23:723–728.
25. O'Holleran JD, Altchek DW. Elbow arthroscopy: treatment of the thrower's elbow. *Instr Course Lect.* 2006; 55:95–107.
26. Rahusen FTG, Brinkman JM, Eygendaal D. Results of arthroscopic debridement for osteochondritis dissecans of the elbow. *Br J Sports Med.* 2006; 40:966–969.
27. Savoie FH III. Guidelines to becoming an expert elbow arthroscopist. *Arthroscopy.* 2007; 23:1237–1240.
28. Steinmann SP. Elbow arthroscopy: where are we now? *Arthroscopy.* 2007; 23:1231–1236.
29. Nakagawa Y, Matsusue Y, Ikeda N, *et al.* Osteochondral grafting and arthroplasty for end-stage osteochondritis dissecans of the capitellum: a case report and review of the literature. *Am J Sports Med.* 2001; 29:650–655.
30. • Iwasaki N, Kato H, Kamishima T, *et al.* Donor site evaluation after autologous osteochondral mosaicplasty for cartilaginous lesions of the elbow joint. *Am J Sports Med.* 2007; 35:2096– 2100.

This study first clarifies no adverse effects of osteochondral graft harvest on donor knee function following mosaicplasty for capitellar OCD in young athletes.

Interlocking intramedullary nailing for nonunion of the proximal humerus with the Straight Nail System

Shintaro Yamane, MD, PhD, Naoki Suenaga, MD, PhD, Naomi Oizumi, MD, PhD, and Akio Minami, MD, PhD, *Sapporo, Japan*

Nonunion of the proximal humerus is a challenging problem. Since 1996, we have performed interlocking intramedullary nailing for the treatment of proximal humeral nonunions with the Straight Nail System and bone grafting. The objective of this study was to investigate the clinical outcomes of this procedure in patients with proximal humeral nonunion. We investigated 14 consecutive patients (mean age, 74.3 ± 8.7 years). One patient was excluded because of associated brachial plexus palsy. All but 2 were initially treated conservatively. Range-of-motion exercises were started 1 week after the operation. The mean follow-up period was 37.8 months. Union was achieved in all cases without any evidence of malunion. All patients had improved range of motion of the shoulder and were satisfied with the surgical results. Mean flexion of the shoulder was 122° ± 14°, and mean external rotation was 35° ± 10°. Interlocking intramedullary nailing with the Straight Nail System and bone grafting offered a successful method of stable internal fixation in these complex proximal humeral nonunion cases. (J Shoulder Elbow Surg 2008;17:755-759.)

Treatment of proximal humeral nonunion is one of the most difficult problems in shoulder surgery. Various surgical procedures have been reported for their treatment.[4,6,8,9,15,17] However, stable fixation is often difficult because of the small proximal articular fragment and osteoporosis. With cavitation of the humeral head fragment as a result of severe bone loss, internal fixation becomes more difficult. Severe contracture of the glenohumeral joint as a result of long-term disuse of the affected shoulder is another common obstacle to achieving a good functional outcome after surgery.[12,16] Therefore, early motion exercises with stable fixation of the fracture site are necessary to obtain good clinical results.

Since 1996, we have performed interlocking intramedullary nailing with bone grafting to treat proximal humeral nonunion, using the Straight Nail System (Nakashima Medical, Okayama, Japan). The purpose of this study was to evaluate the short-term clinical results of interlocking intramedullary nailing with the Straight Nail System in the treatment of proximal humeral nonunion.

MATERIALS AND METHODS

Fourteen consecutive patients with pain and functional impairment due to proximal humeral nonunion were treated operatively by use of an interlocking intramedullary nail with the Straight Nail System between 1996 and 2003 (Table I). After the exclusion of 1 patient who had a brachial plexus palsy at the time of the accident, 13 patients were followed up retrospectively. There were 6 women and 7 men. The mean age at surgery was 74.3 years (range, 60-90 years).

Surgical neck nonunion developed after a 2-part surgical neck fracture in 12 cases and a 3-part surgical neck and greater tuberosity fracture in 1 case. All fractures were closed injuries. The causes of initial injury were a fall from a standing height in 11 patients, a motorcycle accident in 1, and a fall during work on a fishing vessel in 1. The initial treatment consisted of immobilization in a sling followed by physical therapy in 11 patients, closed reduction and percutaneous pinning in 1, and internal fixation with an interlocking intramedullary nail with the Polarus Humeral Nail System (Acumed, Hillsboro, OR) in 1. Only 2 patients had undergone previous operations. Three cases had an associated cavitation of the humeral head at the nonunion site. The mean delay from the injury to surgical treatment was 7 months (range, 3-17 months). One case was recognized as a nonunion at 3 months after injury, because a distinct cavitation of the humeral head with severe bone atrophy was found at that time. All patients complained of pain at the nonunion site; limitation of shoulder movement, particularly with overhead activities; and difficulty in carrying out daily activities. The exact range of glenohumeral movement was difficult to estimate because of pain and mobility at the pseudarthrosis. The mean preoperative active flexion and external rotation of the upper arm were 38° (range, 20°-45°) and 15° (range, 0°-30°), respectively.

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Table I Patient data

Case No.	Age (y)	Sex	Side	Fracture type	Initial treatment	Delay between injury and operation (mo)	Humeral head cavitation	Complications	Follow-up (mo)	Final active flexion (°)	Final external rotation (°)	JOA score
1	90	M	R	Surgical neck	Conservative	3	+		24	100	25	86
2	79	F	L	Surgical neck	Conservative	10		Screw loosening	42	125	35	92
3	77	F	L	Surgical neck	Percutaneous pinning	10			36	125	45	89
4	60	F	R	Surgical neck	Conservative	7			42	150	60	97
5	74	M	L	Surgical neck	Conservative	5			36	140	45	94
6	64	M	R	3-Part greater tuberosity	Conservative	5	+	Screw loosening	40	100	20	86
7	66	M	R	Surgical neck	Conservative	5	+		18	120	35	92
8	82	M	L	Surgical neck	Polarus nail	17			34	115	35	84
9	81	M	R	Surgical neck	Conservative	8			58	130	40	84
10	73	F	L	Surgical neck	Conservative	6			44	125	30	83
11	76	F	R	Surgical neck	Conservative	6			41	120	30	79
12	66	F	R	Surgical neck	Conservative	10			40	130	30	85
13	80	M	R	Surgical neck	Conservative	9			36	110	25	71

The Straight Nail System was originally developed for fixation of proximal humeral fractures. The nail is solid and straight. Its diameter is 9 mm. The insertion point of the straight nail is close to the top of the humeral head; therefore, this system is less damaging to the rotator cuff. In a 3- or 4-part fracture, it is possible to fix the humeral head fragment with the intramedullary nail. Moreover, in proximal humeral nonunions, 2 proximal interlocking screws are available even for a humeral head with cavitation.

Surgical technique

The operation was performed with the patients placed in the beach-chair position under general anesthesia with interscalene nerve block. The nonunion site was explored through the deltopectoral approach. After removal of scar tissue at the nonunion site, a longitudinal incision was made in the supraspinatus muscle through a deltoid splitting approach, and an osteochondral fragment was removed from the nail insertion site on the humeral head. The nail (9 mm in diameter) was inserted gently from near the top of the humeral head. After insertion of the nail, a proximal interlocking screw was inserted from the lateral aspect of the humeral head. Next, 2 or 3 distal interlocking screws were inserted at the deltoid insertion to avoid radial nerve injury. Finally, another proximal interlocking screw from anterior to posterior and an end cap were placed. The removed osteochondral fragment was returned to its original site. Autologous iliac bone graft was placed at the nonunion site to fill the defect in 10 cases. In 4 cases in which the defect was small, alpha–tricalcium phosphate paste, as artificial bone with local cancellous bone, was grafted without harvesting of iliac bone.

After surgery, the patient's arm was immobilized in a sling and swathe. Postoperative passive range-of-motion (ROM) exercises were started 1 week after surgery. Active ROM exercises were allowed at 4 weeks postoperatively.

At the final follow-up examination, all cases were evaluated by use of the shoulder score of the Japanese Orthopaedic Association (JOA). The JOA score includes the level of shoulder pain (30 points), function (20 points), ROM (30 points), radiologic findings (5 points), and joint stability (15 points). The maximum possible overall score is 100 points. In this study, outcomes were classified based on the JOA score as excellent (≥91 points), good (81-90 points), fair (71-80 points), or poor (≤70 points). We also evaluated the union of the fracture and complications. Radiographic outcome measurements included alignment changes of the fracture, hardware failure, avascular necrosis of the humeral head, malunion, and nonunion. Union was defined as occurring when continuation of the cortical bone was visible on at least 2 different radiographic views. The mean time from

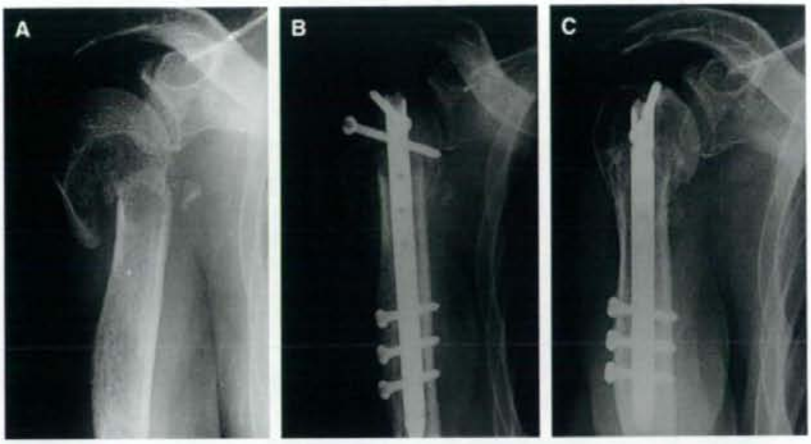

Figure 1 Case 6. **A**, Preoperative radiograph of nonunion with cavitation in 64-year-old man (5 months after initial injury). **B**, The surgical neck nonunion with cavitation was treated with the Straight Nail System and iliac cancellous bone graft. **C**, Although 1 of the proximal interlocking screws backed out and was removed, the nonunion site was well united without malunion (40 months after surgery).

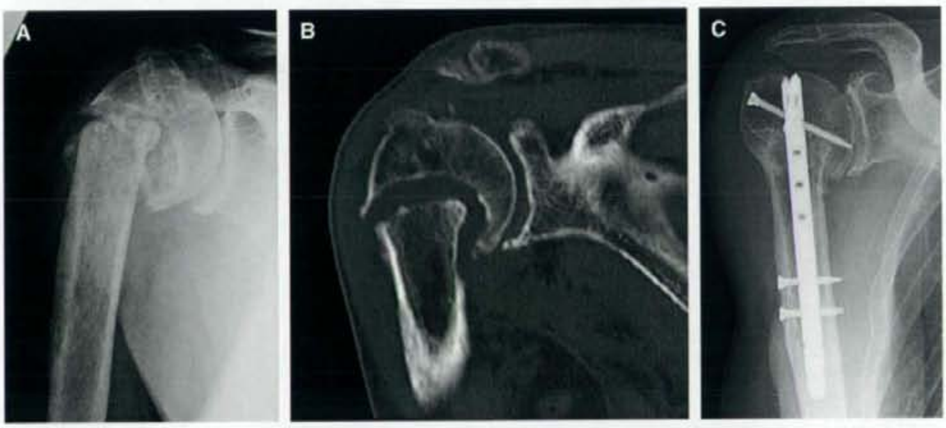

Figure 2 Case 7. **A**, A 66 year-old man had a surgical neck nonunion 5 months after an accident on a fishing vessel. **B**, The preoperative computed tomography image showed cavitation of the humeral head fragment. **C**, At 12 months after surgery, he had no complaints and had returned to full duties on the fishing vessel.

surgery for the proximal humeral nonunion to the final follow-up was 37.8 months (range, 18-58 months).

RESULTS

Union was confirmed without any malunion in all cases, and no necrosis of the humeral head was observed (Figures 1 and 2). The mean time to union was 4 months (range, 3-5 months). The symptoms improved in all cases after surgery, and all patients were satisfied with the results. The mean JOA score was 85 points (range, 71-97 points) at the final follow-up. Excellent results were obtained in 4 shoulders, good in 7, and fair in 2. Postoperative ROM of the shoulder was improved in all cases. Postoperatively, mean flexion was 122° (range, 100°-150°) and mean external rotation was 35° (range, 20°-60°). Backing out of the proximal interlocking screw occurred in 2 cases, and the screw was subsequently removed. There were no cases of infection, nerve injury, ectopic ossification, avascular necrosis, or implant failure.

DISCUSSION

Nonunion of the proximal humerus results in severe disability because of pain and instability. Moreover, patients often have marked contracture of the glenohumeral joint because of prolonged immobilization of the shoulder. In 1983, Neer[11] outlined the difficulties of treating nonunion in cases with severe osteoporosis and bone cavitation. When nonunion of the proximal humerus occurs in the elderly patient, it commonly presents with insufficient bone stock, severe bony resorption, and cavitation of the humeral head.

Many approaches to the treatment of proximal humeral nonunions have been reported, including intramedullary rods, rods with tension bands,[3,9,11,12] plate fixation,[5-7,14] intramedullary cortical bone strut grafts,[17] and hemiarthroplasty.[2,3,6,9] In the results of the previously reported procedures, various problems have been pointed out. Plate fixation is suitable for patients with sufficient bone stock in the humeral head[6,15] and is also acceptable if large cavitation is present, if a large iliac bone peg is grafted.[17] However, this procedure has the disadvantage of extensive soft-tissue dissection, inadequate screw fixation on the humeral head, avascular necrosis of the humeral head,[10] and mechanical impingement underneath the acromion.[4] Although an intramedullary rod, with or without tension-band wiring, requires less soft-tissue dissection compared with plating techniques, it also causes mechanical impingement.[3,6,9] In addition, a second operation to remove the implant is usually necessary.[6,9,12] Hemiarthroplasty is effective for pain relief, but sometimes functional recovery is not satisfactory.[3,6,9] Recently, several kinds of interlocking intramedullary nails have been developed for proximal humeral fractures.[1,13] Interlocking intramedullary nails provide good antirotational stability with transfixing screws. Lin and Hou[8] reported on 15 patients treated with interlocking intramedullary nails for painful nonunions of the proximal humerus. Bone union was achieved in 14 of 15 patients, and 13 had excellent or good functional recovery. They reported that the mean ROM of patients with excellent or good functional recovery (2 patients were excluded) was 152.3° in flexion and 146.4° in abduction. However, the mean age of their patients was 55.1 years (as compared with 74.3 years in our study), and 1 patient did not achieve osseous union. In comparing postoperative rehabilitation programs, Walch et al[17] reported that the patients' arms were immobilized by a sling for 30 days and active motion of the shoulder was not allowed until at least 3 months after intramedullary cortical bone strut grafting with plate fixation. However, the postoperative immobilization period was shorter in recent reports. Galatz et al[5] reported that passive ROM of the shoulder was allowed immediately after plate fixation. Lin and Hou reported that ROM exercise was encouraged as early as tolerable after interlocking intramedullary nail fixation. In our study, we allowed passive ROM of the shoulder 1 week after surgery, because it was not easy for elderly patients to start aggressive ROM exercises within a few days after surgery.

Cancellous bone graft harvested from iliac crest was added to the nonunion site in most reports of proximal humeral nonunion. In our patients, bone union was achieved with artificial bone and local bone grafts in 4 recent cases. This was because the bone loss was not large, and the intramedullary nail itself occupied the center of the bone loss where iliac bone would have been placed. It also suggests that the nonunion site had stable fixation with the Straight Nail System. Moreover, in our study, 3 cases had severe cavitation in the humeral head fragment. Although early motion exercise was permitted after surgery, all patients, including those with cavitation, obtained complete union. All were able to elevate their arms above the shoulder level, and half of them were able to elevate more than 120°. Although there were some who had limited ROM, all patients were satisfied with the final ROM and had no difficulty in performing activities of daily living. One of the reasons for residual ROM restriction was that most cases in this study were initially treated conservatively. Therefore, their arms were immobilized for some time before being treated surgically. In addition, most were older patients, and it was difficult to perform aggressive rehabilitation.

The advantages of this system are that the nail can fix nonunion sites with 2 proximal interlocking screws, even in the presence of a humeral head with cavitation, and that it is less invasive to the rotator cuff tendons compared with the other angulated nails that are inserted through the cuff, because the nail in this system is straight and is inserted through the cuff muscle. On the other hand, damage to the articular surface is a disadvantage. However, the removed osteochondral fragment was returned to the original site, and no case showed severe progression of osteoarthritis during the follow-up period.

This study has several weaknesses. The investigation was retrospective, and there was no comparison to other treatment methods. Moreover, the study group was small, and long-term follow-up will be needed to assess the incidence of osteoarthritic change. Although there are considerable limitations, as mentioned previously, the clinical and radiographic results of this study suggest that interlocking intramedullary nailing with the Straight Nail System is a reasonable option for treating proximal humeral nonunion, especially in cases with osteoporosis and cavitation.

REFERENCES

1. Adedapo AO, Ikpeme JO. The results of internal fixation of three- and four-part proximal humeral fractures with the Polarus nail. Injury 2001;32:115-21.
2. Antuna SA, Sperling JW, Sanchez-Sotelo J, Cofield RH. Shoulder arthroplasty for proximal humeral nonunions. J Shoulder Elbow Surg 2002;11:114-21.
3. Duralde XA, Flatow EL, Pollock RG, Nicholson GP, Self EB, Bigliani LU. Operative treatment of nonunions of the surgical neck of the humerus. J Shoulder Elbow Surg 1996;5:169-80.
4. Galatz LM, Iannotti JP. Management of surgical neck nonunions. Orthop Clin North Am 2000;31:51-61.
5. Galatz LM, Williams GR Jr, Fenlin JM Jr, Ramsey ML, Iannotti JP. Outcome of open reduction and internal fixation of surgical neck nonunions of the humerus. J Orthop Trauma 2004;18:63-7.
6. Healy WL, Jupiter JB, Kristiansen TK, White RR. Nonunion of the proximal humerus. A review of 25 cases. J Orthop Trauma 1990;4:424-31.
7. Jupiter JB, Mullaji AB. Blade plate fixation of proximal humeral non-unions. Injury 1994;25:301-3.
8. Lin J, Hou SM. Locked-nail treatment of humeral surgical neck non-unions. J Trauma 2003;54:530-5.
9. Nayak NK, Schickendantz MS, Regan WD, Hawkins RJ. Operative treatment of nonunion of surgical neck fractures of the humerus. Clin Orthop Relat Res 1995:200-5.
10. Neer CS II. Displaced proximal humeral fractures. II. Treatment of three-part and four-part displacement. J Bone Joint Surg Am 1970; 52:1090-103.
11. Neer CS II. Nonunion of the surgical neck of the humerus. Orthop Trans 1983;7:389.
12. Norris TR, Turner JA, Bovil D. Nonunion of the upper humerus: an analysis of the etiology and treatment in 28 cases. In: Post M, Morrey BF, Hawkins RJ, editors. Surgery of the shoulder. St Louis: Mosby Year-Book; 1990. p. 63-7.
13. Rajasekhar C, Ray PS, Bhamra MS. Fixation of proximal humeral fractures with the Polarus nail. J Shoulder Elbow Surg 2001;10: 7-10.
14. Ring D, McKee MD, Perey BH, Jupiter JB. The use of a blade plate and autogenous cancellous bone graft in the treatment of ununited fractures of the proximal humerus. J Shoulder Elbow Surg 2001; 10:501-7.
15. Scheck M. Surgical treatment of nonunions of the surgical neck of the humerus. Clin Orthop Relat Res 1982:255-9.
16. Volgas DA, Stannard JP, Alonso JE. Nonunions of the humerus. Clin Orthop Relat Res 2004:46-50.
17. Walch G, Badet R, Nove-Josserand L, Levigne C. Nonunions of the surgical neck of the humerus: surgical treatment with an intramedullary bone peg, internal fixation, and cancellous bone grafting. J Shoulder Elbow Surg 1996;5:161-8.

In vitro and finite element analysis of a novel rotator cuff fixation technique

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The purpose of this investigation was to assess the biomechanic strength and stress dispersion at the repair site of surface-holding repair techniques for rotator cuff repair compared to the double-row technique. Eighteen bovine infraspinatus tendons were repaired using 3 different repair techniques: double-row repair, surface-holding repair with transosseous sutures, and surface-holding repair with knotless anchors. Biomechanical testing and two-dimensional finite element analysis were performed. The surface-holding repair with transosseous sutures provided 87.9% more stiffness than the double-row repair. The number of tendon-suture site failures of the surface-holding repair with transosseous sutures was smaller than the other 2 techniques. The finite element analysis showed that the surface-holding repair model had a more dispersing stress pattern compared to a double-row repair model. It suggests that these repair techniques can prevent high stress concentration compared to the double-row repair. (J Shoulder Elbow Surg 2008;17:986-992.)

Despite excellent clinical results of open or arthroscopic rotator cuff repair, some studies have reported a relatively high percentage of re-rupture after rotator cuff repair.[8,9,11-13,18] Recent work has suggested that the most common failure mode was the tendon-suture site in rotator cuff repairs with suture anchors and horizontal mattress sutures.[6] Cummins and Murrell reported that 19 of 22 revision rotator cuff repairs using suture anchors failed because of tendon pulling through sutures.[6] They concluded that the weakest link in rotator cuff repair with suture anchors was the tendon-suture interface. It has been found that load-sharing and stress distribution in the tendon are implicated in maintaining cuff integrity until biological healing.[2,10,27] Burkhart et al reported that load-sharing by multiple suture tails and multiple knots in the simple suture configuration contributed to its superior strength compared with the mattress suture configurations.[2] Sano et al reported on the stress distribution at the repaired tendon site with use of finite element methods.[27] They suggested that high stress concentration might cause the re-tear observed after arthroscopic cuff repair using suture anchors. Therefore, we assume that stress dispersion at the tendon-suture interface could be a way to solve the tendon site re-tear problem.

Our strategy for accomplishing a wide contact-area and stress dispersion entails holding the footprint surface by multiple suture threads without a complicated suture technique. Two different techniques have been developed with this strategy. One technique employed a modification of that proposed by Waltrip et al, who used medial anchors and lateral transosseous sutures.[30] The other, using knotless anchors for the lateral row fixation, was developed using the same strategy, especially for arthroscopic rotator cuff repair. We hypothesized that these surface-holding repair techniques of rotator cuff repair would provide a different failure mode biomechanically, as well as substantial stress dispersion at the repair site compared to the double-row repair technique. To investigate these hypotheses, an *in vitro* biomechanical examination was performed using bovine shoulders. Stress distribution inside the repaired tendon was assessed using two-dimensional (2D) finite element (FE) models. The purposes of the current study were 1) to evaluate the initial strength and the failure mode of a double-row repair technique and these surface-holding techniques, and 2) to compare the stress distribution of the surface-holding repair model with that of a double-row repair model using 2D FE analyses.

MATERIALS AND METHODS

Eighteen fresh frozen bovine shoulders were randomly assigned to 3 fixation groups (6 per group) and used for biomechanical testing of rotator cuff repair model.[5,16,17,25] The

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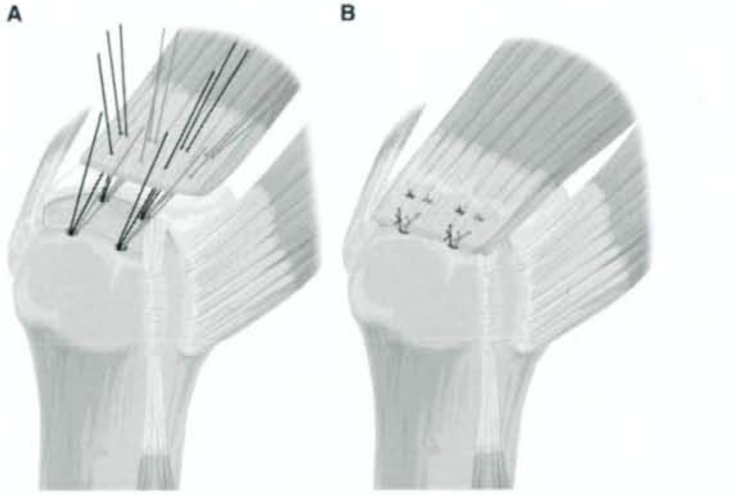

Figure 1 These figures recreated the normal supraspinatus tendon-bone interface with use of double-row repair technique. **A**, Two medial anchors were placed adjacent to the humeral articular cartilage after decortication. Two lateral anchors were separated approximately 20 mm lateral to the medial anchors. Eight threads in the medial row and 4 threads in the lateral row were passed through the supraspinatus tendon. **B**, Four horizontal mattress suture configurations for the medial row and 4 simple suture configurations for the lateral row were performed in the double-row repair.

bovine infraspinatus tendon was chosen for its appropriate size and the secure fixation of suture anchors as necessary for biomechanical evaluation at averaged tendon-suture interface. Arthroscopic knot tying was performed for all techniques using Samsung Medical Center (SMC) knots with 2 half hitches.[15]

A double-row repair fixation, using 4 metal 5.0 mm anchors (Fastin; Mitek, Norwood, MA) loaded with double No. 2 braided polyester sutures (Ethibond; Ethicon, Somerville, NJ), was used for a control (Figure 1, *A, B*). Two medial anchors were placed on cancellous bone. Two lateral anchors were separated approximately 20 mm lateral to the medial anchors. Four horizontal mattress suture configurations for the medial row and 4 simple suture configurations for the lateral row were performed in the double-row repair.

Two different techniques were considered for surface-holding: the surface-holding repair technique with transosseous sutures, which modified the anatomic double-layer repair with use of transosseous sutures and suture anchors,[30] and the usage of Fastin anchors for medial row anchors. These anchors were placed on cancellous bone. Eight threads were passed through the tendon (Figure 2, *A*). For lateral-transosseous fixation, 3 tunnels separated by 15 mm were created from cancellous bone to cortical bone (Figure 2, *B*).

Another technique for stress dispersion was developed using the same strategy for an arthroscopic procedure. Double loops of No. 1 Ethibond were loaded in a Fastin anchor instead of the original suture thread. These 2 Fastin anchors were used for medial row anchors. Four self-locking bioabsorbable anchors (Bioknotless RC; Mitek, Raynham, MA), loaded with double No. 1 Ethibond sutures, were used as lateral row anchors. Four loops of the medial anchors were passed through the tendon (Figure 3, *A*). After each loop was hooked using a Bioknotless RC anchor, the anchor was placed on cancellous bone in a lateral row. The tendon stump was compressed onto the tuberosity by 4 loops (Figure 3, *B*).

A bone-tendon preparation was mounted and attached to a conventional tensile tester (Shimadzu, Kyoto, Japan). The humerus was rigidly constrained in a metal frame. The free end of the tendon was firmly gripped at the distal aspect of a clamp. The mechanical testing protocol was based on a previous report.[7] After applying a preload of 5 N for 10 minutes, tensile tests in all specimens were performed at a cross-head speed of 20 mm/min. Each shoulder's failure mode was recorded. Linear stiffness was defined by the slope of the load-deformation curve, which was determined by a least-squares linear regression analysis of the data between the end point of the toe region and that point starting to bend before failure. The mean ultimate load and linear stiffness were statistically compared among the 3 groups, using one-way analysis of variance (ANOVA) and Fisher's PLSD *post hoc* test. Statistical significance was set at $P < .05$.

FE models were developed based on previous reports using the commercial software MENTAT 2005 (MSC Software Japan Ltd, Tokyo, Japan).[26,27,29] A 2D FE model of the supraspinatus tendon attached to the humerus was originally developed using a magnetic resonance image (MRI) of the normal human shoulder.[29] By modifying this model, supraspinatus tendon repair with various suture techniques were simulated in our previous study.[27]

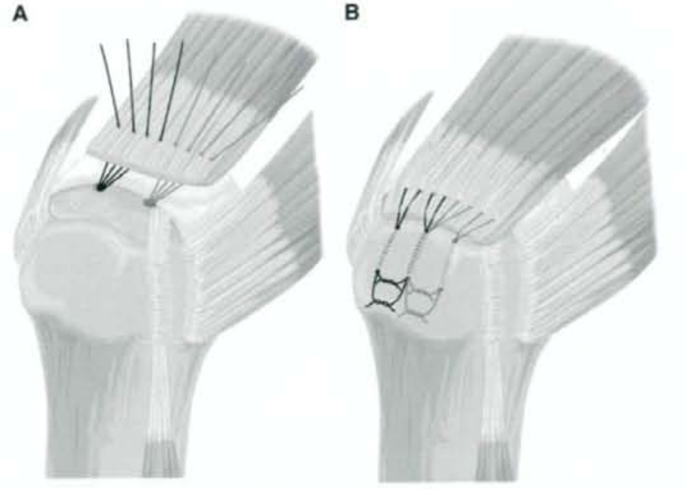

Figure 2 These figures recreated the normal supraspinatus tendon-bone interface with use of surface-holding repair technique with transosseous sutures. **A**, Two medial suture anchors were placed adjacent to the humeral articular cartilage after decortication. Eight threads were passed through the supraspinatus tendon. **B**, Typical transoseeous sutures with 3 drill holes were used for the fixation.

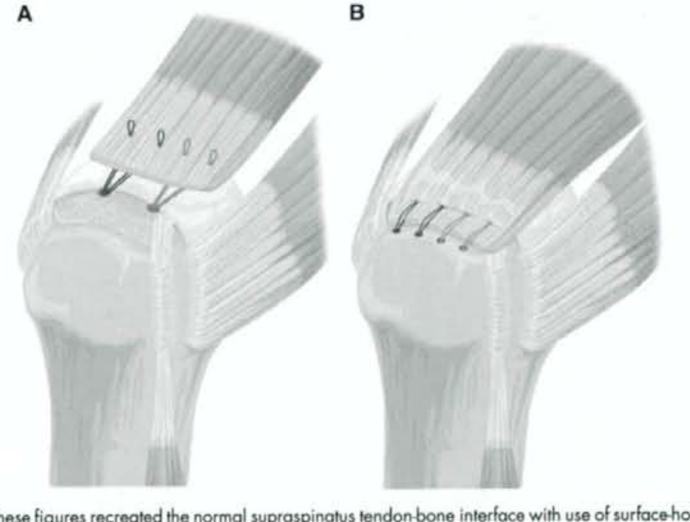

Figure 3 These figures recreated the normal supraspinatus tendon-bone interface with use of surface-holding repair technique with knotless suture anchors. **A**, Two medial suture anchors were placed adjacent to the humeral articular cartilage. Four loops were passed through the supraspinatus tendon. **B**, After the loops were hooked using Bioknotless RC anchors, the anchors were placed on appropriate quality bone in a lateral row. The tendon stump was compressed onto the tuberosity by 4 loops.

The model consisted of 5 types of tissue having different material properties, including tendon proper, articular cartilage, cancellous bone, subchondral bone, and cortical bone. Young's modulus and Poisson's ratio of those types of tissues were determined based on our previous study (Table I). The abduction angle of the glenohumeral joint was fixed at 0° degrees and thickness of the models was determined as 21.9 mm, which corresponded to the width of the normal supraspinatus tendon. The distal part of the humeral head was fixed both in x and y directions. Based

Table I Material properties of each type of tissue in current models

	Young's modulus (MPa)	Poison's ratio
Supraspinatus tendon	168	0.497
Articular cartilage	35	0.450
Cancellous bone	1,380	0.300
Subchondral bone	2,780	0.300
Cortical bone	13,800	0.300

on these experiences, we developed the double-row repair and surface-holding repair models to simulate the double-row repair and the and with knotless anchor, respectively. Because both surface-holding with transosseous suture and knotless anchor included no medial knot and holding the tendon stump with the sutures, we considered the model of these repair techniques to be identical from the point of stress distribution. In the surface-holding repair model, the torn surface of the tendon stump was designed to face the footprint, simulating the effect of lateral fixation. The CONTACT is a mode of setting the contact conditions in commercial software, MENTAT 2005 and MARC 2005 (MSC Software Japan Ltd, Tokyo, Japan). In this model, the articular surface of the supraspinatus tendon and humeral head were defined as contact bodies. The friction coefficient between the contact bodies was determined as 0. A tensile load of 10 N was gradually applied to the proximal end of the supraspinatus to simulate its contraction force. We hypothesized that suture repair could be recreated in the FE models using the glue of the elements on the tendon stump with that on the bony surface, as previously described.[27] The glue is one of the functions of the Boolean operation to build an FE model. Adjacent entities are glued, and a new entity set is created. In our model, glue function was used simply to simulate the suture site. That is, in the double-row model, the articular surface of the tendon and the surface of the greater tuberosity were glued at 2 points to simulate 2 suture anchors. In the surface-holding repair model, 2 points were also glued to simulate an anchor at the proximal site and a suture thread at the distal site (Figure 4, *A*, *B*). The width of each glued element was controlled as approximately 0.5 mm to simulate the diameter of No. 2 suture thread. For the double-row repair model, the medial and lateral rows were glued at the footprint. In the surface-holding repair model, the superficial and deep rows were glued at the footprint. Park et al[23] reported the mean interface pressure exerted over the footprint with the double-row repair technique was 0.19 MPa.

In this study, we estimated that 20 mm of No. 2 Ethibond provided 10 mm^2 of actual contact area. We hypothesized 2 N of the compression force based on these data; therefore, in the double-row repair model, a load of 2 N was applied on 2 points on the surface of the tendon simulating sutures (Figure 4, *A*). To define the stress distribution inside the repaired tendon with the surface-holding repair model, we hypothesized that the counter force of the suture has the opposite direction of muscle contraction when the glenohumeral angle was 0 degrees. Therefore, the direction of the compressive force from the sutures to inside the tendon stump was determined as 2 N for the 45° minus-*x* and the 45° minus-*y* directions in the surface-holding repair model (Figure 4, *B*). The distribution of the von Mises stress was calculated by MARC 2005.

RESULTS

Biomechanical testing

We found that 66.7 % (4 of 6 specimens) failed at the tendon-suture interface in the double-row repair and the surface-holding with knotless anchor. In the surface-holding with transosseous suture, 33.3% (2 out of 6) failed at tendon-suture interface. The percentage of the failure at tendon-suture site in the surface-holding with transosseous suture was 50% less than that in the other groups (Table II). The surface-holding with transosseous suture provided almost the same ultimate strength as the double-row repair (Table III). There were no significant differences among the ultimate strength of the 3 groups. Although no significant difference in linear stiffness was found among the 3 groups, the surface-holding with transosseous suture provided 87.9% more stiffness than the double-row repair (mean, 43.4 N/m vs. 23.1 N/m, $P = .0872$). However, there may not have been a large enough sample size to detect a difference between the 2 groups, if a difference existed. Further studies should be conducted.

Finite element analyses

In the double-row repair model, the highest von Mises stress was seen on the acromial surface of the repaired tendon near the medial row sutured, and little stress was observed on the stump of the repair tendon (Figure 5, *A*). In the surface-holding repair model, mild stress was distributed throughout the repaired tendon. No obvious stress concentration was observed on the tendon stump (Figure 5, *B*). The maximum von Mises stress was found around the superficial layer on the acromial surface of the repaired tendon in the surface-holding repair model. The highest von Mises stress (1.425e + 00) in the surface-holding repair model was 23.7% less than that in the double-row repair model (6.007e +00) at the site of repair.

DISCUSSION

We believe that a favorable repair technique could accomplish stress dispersion at the tendon-to-bone interface. Our concept entails holding the footprint surface by many suture threads without a complicated suture technique to maintain cuff integrity. The surface-holding with transosseous suture provided such a tendency with 50% less failure at the tendon-suture site and 87.9% more stiffness than the double-row repair. The increased stiffness and decreased number of the failures at the tendon-suture site would help us

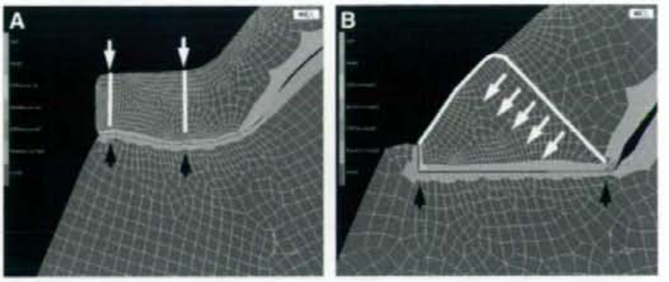

Figure 4 Contact conditions of the repair site for the *double-row repair model* (**A**) and the *surface-holding repair model* (**B**). A narrow gap (0.025 mm) was created between the tendon stump and the bony surface of the greater tuberosity. Glue elements were shown with black arrows. Stitches were shown with white lines. The direction of the counter force of the stitch was shown with white arrows.

Table II Results of tensile testing: Failure mode

	Failure Mode (%)		
	Double-row repair	**Surface-holding transosseous**	**Surface-holding knotless**
Tendon to suture	66.7	33.3	66.7
Suture breakage	33.3	0	0
Bone cutout	0	50	0
Anchor pullout	0	16.7 [a]	33.3 [b]

n = 6.

[a]One out of six anchors was pullout at the medial side anchor.

[b]Two out of six anchors were at the lateral side anchor.

Table III Results of tensile testing: Ultimate load and stiffness

	Double-row repair	**Surface-holding transosseous**	**Surface-holding knotless**
Ultimate load (N)	328.6 ± 32.6	352.9 ± 25.1	260.9 ± 46.8
Linear stiffness (N/m)	23.1 ± 6.4	43.4 ± 11.5 [a]	22.7 ± 3.3

There were no statistically significant differences for ultimate load in all groups ($P > .05$).

n = 6, mean ± SEM.

[a]The surface-holding with transosseous provided a tendency with 87.9% more stiffness than the double-row repair ($P = .087$)

improve the tissue-holding strength of the sutures in the surface-holding with transosseous.

Several techniques of holding a broad surface of the repaired tendon have been reported previously.[1,4,19,20,22,24] Millett et al have developed the mattress double anchor (MDA) technique.[20] Their concept of holding the tendon stump is similar to our strategy. Recently, the same investigating group reported the ultimate load had no significant difference between the MDA and a diamond shaped double-row repair with 2 medial mattress and 4 lateral simple suture, similar to the present study.[19] Park et al reported that the transosseous-equivalent rotator cuff repair improved ultimate loads, compared with a double-row technique with 2 medial mattress sutures and 2 lateral simple sutures.[24] Our double-row repair with 4 mattress sutures and 4 simple sutures includes a greater number of suture configurations, 8, compared to their double-row techniques. This may be the main reason that we could not find significant differences between the double-row repair and surface-holding with transosseous suture in this study. As the biomechanical conditions of these prior 2 studies were different from those of the current study, it would be difficult to compare the biomechanical results. However, we could conclude that the ultimate load in the surface-holding with transosseous suture was equally as high as that in the double-row repair.

In FE analysis, realistic conditions should be simulated using a simple model. Comparing the stress distribution between a standard double-row repair model and our surface-holding repair model, we focused on simplifying these models' respective designs.[27] In the double-row repair model, the highest stress was seen on the subacromial, bursal side of the repaired tendon near the medial row sutured part. This result was consistent with previous *in vitro* and *in vivo* biomechanical reports of the failure mode of rotator cuff repair.[6, 14, 21] Residual tensile strain on the subacromial bursal surface of the supraspinatus tendon was greater than that of the deeper regions of the tendon in the double-row repair.[14] In contrast, the FE analysis showed no obvious stress concentration in the surface-holding repair model. In the previous FE model, the high stress concentration appeared at the attachment site inside the bony trough in a simple transosseous model.[27] Relatively low stress concentration was seen in the tendon's

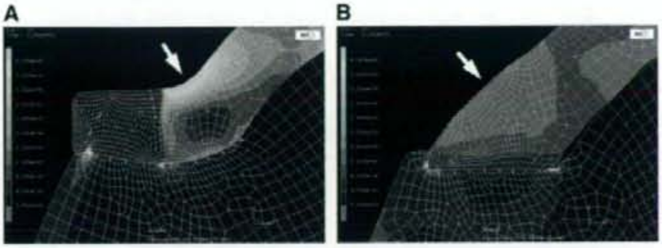

Figure 5 Stress distribution at the repair site in each model in two-dimensional finite element analyses. **A**, Double-row repair model: the highest von Mises stress was seen on the acromion surface of the repaired tendon near the medial row sutured part (*white arrow*). Little stress was observed on the stump of the repair tendon. **B**, Surface-holding repair model: Mild stress was distributed throughout the repaired tendon. No obvious stress concentration was observed on the tendon stump. The highest von Mises stress was found on the acromion surface around the superficial layer (*white arrow*). The highest von Mises stress (1.425e + 00) in the surface-holding repair model was 23.7% less than that in the double-row repair model (6.007e +00) at the site of repair.

articular and bursal sides. The medial row anchor, simulated as glue, distributed the stress pattern at the articular site. The compression force simulated the suture over the tendon stump and spread out the stress at the bursal side. This compression force would help the torn surface of the tendon stump to face and to be flush with the bony trough. This more physiological footprint reconstruction may facilitate a more dispersed stress pattern inside the tendon, compared with the double-row repair model.

This FE analysis has several drawbacks in the process of modeling, including design of the models, definition of the boundary conditions, material properties, and contact conditions. In the surface-holding repair model, we applied a compressive load (2N) at the distal end of the tendon stump. As no data were available concerning the compressive load created by a lateral row, the value of 2N was determined based on a previous report[23]; however, the compressive load would have a wide range for various clinical conditions. The option of glue of the elements was used to recreate the suture anchor repair in the current FE model. The protocol, including all factors, is too complicated to be practicable in this model. However, all these assumptions might affect the analyses results.

We developed a surface-holding technique with knotless anchors for arthroscopic procedures, because a transosseous technique would be complicated for arthroscopic surgery. The biomechanical evaluation showed that the surface-holding with knotless anchor has 26% less ultimate strength than the surface-holding with transosseous. The failure mode of the surface-holding with knotless anchor included 4 cases of tendon-suture site and 2 cases of lateral knotless anchors pullout. The loop in the surface-holding with knotless anchor may have insufficient intervals between each side of the loop; therefore, the biomechanical contribution of 1 loop may be similar to 1 simple suture. This means that the loops could not produce enough horizontal stress dispersion. The other important factor for fixation with suture anchors would be the fixation-strength of anchors. The screw-in anchors were significantly stronger than biodegradable anchors in areas in which bone mineral density was low in a human cadaveric model.[28] Although the lateral anchors in the surface-holding with knotless anchor were used for biodegradable self-locking anchors, another anchor type may be considered. In addition, the location of the lateral-anchor position should take bone quality into account. It was not possible to establish the best position of lateral anchors in the current study. The knotless anchors technique could be used for a good bone quality case.

There are some limitations in this study. One was using bovine shoulders. The healthy infraspinatus tendons differ from the degenerated tendons seen in human shoulders with chronic rotator cuff tears. Therefore, it may not directly correlate to human clinical conditions. Although the degenerative tendon model should be evaluated, one of the problems in human cadavers is the wide variety of cuff tendons. Another limitation is that a cyclic load test was not performed in this study. Burkhart et al stated that cyclic loading is the mechanism by which rotator cuff fixation failure occurs *in vivo*.[3] Cyclic loading testing should be examined in future studies. The other limitation of our study is the small number of bovine shoulder specimens tested. Although we found no significant difference among the 3 groups, the effect size at which the study would be sufficiently powered may be larger than a clinically significant difference.

In summary, we have shown that the surface-holding repair technique with transosseous sutures for rotator cuff repair has equally high initial ultimate loads as a standard double-row repair technique. The results of the FE analysis suggest that the surface-holding repair model can provide stress dispersion comparabel to the double-row repair model.

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REFERENCES

1. Arrigoni P, Brady PC, Burkhart SS. The double-pulley technique for double-row rotator cuff repair. Arthroscopy 2007;23(675):e1-4.
2. Burkhart SS, Fischer SP, Nottage WM, Esch JC, Barber FA, Doctor D, et al. Tissue fixation security in transosseous rotator cuff repairs: a mechanical comparison of simple versus mattress sutures. Arthroscopy 1996;12:704-8.
3. Burkhart SS, Johnson TC, Wirth MA, Athanasiou KA. Cyclic loading of transosseous rotator cuff repairs: tension overload as a possible cause of failure. Arthroscopy 1997;13:172-6.
4. Burkhead WZ Jr, Skedros JG, O'Rourke PJ, Pierce WA, Pitts TC. A novel double-row rotator cuff repair exceeds strengths of conventional repairs. Clin Orthop Relat Res 2007;461:106-13.
5. Coons DA, Barber FA, Herbert MA. Triple-loaded single-anchor stitch configurations: an analysis of cyclically loaded suture-tendon interface security. Arthroscopy 2006;22:1154-8.
6. Cummins CA, Murrell GA. Mode of failure for rotator cuff repair with suture anchors identified at revision surgery. J Shoulder Elbow Surg 2003;12:128-33.
7. Funakoshi T, Majima T, Iwasaki N, Suenaga N, Sawaguchi N, Shimode K, et al. Application of tissue engineering techniques for rotator cuff regeneration using a chitosan-based hyaluronan hybrid fiber scaffold. Am J Sports Med 2005;33:1193-201.
8. Galatz LM, Ball CM, Teefey SA, Middleton WD, Yamaguchi K. The outcome and repair integrity of completely arthroscopically repaired large and massive rotator cuff tears. J Bone Joint Surg Am 2004;86-A:219-24.
9. Gerber C, Fuchs B, Hodler J. The results of repair of massive tears of the rotator cuff. J Bone Joint Surg Am 2000;82:505-15.
10. Gerber C, Schneeberger A, Beck M, Schlegel U. Mechanical strength of repairs of the rotator cuff. J Bone Joint Surg Br 1994;76-B:371-80.
11. Harryman DT II, Mack LA, Wang KY, Jackins SE, Richardson ML, Matsen FA III. Repairs of the rotator cuff. Correlation of functional results with integrity of the cuff. J Bone Joint Surg Am 1991;73:982-9.
12. Jost B, Zumstein M, Pfirrmann CW, Gerber C. Long-term outcome after structural failure of rotator cuff repairs. J Bone Joint Surg Am 2006;88:472-9.
13. Jost B, Pfirrmann CWA, Gerber C. Clinical outcome after structural failure of rotator cuff repairs. J Bone Joint Surg Am 2000;82:304-14.
14. Kim DH, Elattrache NS, Tibone JE, Jun BJ, DeLaMora SN, Kvitne RS, et al. Biomechanical comparison of a single-row versus double-row suture anchor technique for rotator cuff repair. Am J Sports Med 2006;34:407-14.
15. Kim SH, Ha KI. The SMC knot–a new slip knot with locking mechanism. Arthroscopy 2000;16:563-5.
16. Koganti AK, Adamson GJ, Gregersen CS, Pink MM, Shankwiler JA. Biomechanical comparison of traditional and locked suture configurations for arthroscopic repairs of the rotator cuff. Am J Sports Med 2006;34:1832-8.
17. Lee S, Mahar A, Bynum K, Pedowitz R. Biomechanical comparison of bioabsorbable sutureless screw anchor versus suture anchor fixation for rotator cuff repair. Arthroscopy 2005;21:43-7.
18. Liu SH, Baker CL. Arthroscopically assisted rotator cuff repair: correlation of functional results with integrity of the cuff. Arthroscopy 1994;10:54-60.
19. Mazzocca AD, Millett PJ, Guanche CA, Santangelo SA, Arciero RA. Arthroscopic single-row versus double-row suture anchor rotator cuff repair. Am J Sports Med 2005;33:1861-8.
20. Millett PJ, Mazzocca A, Guanche CA. Mattress double anchor footprint repair: a novel, arthroscopic rotator cuff repair technique. Arthroscopy 2004;20:875-9.
21. Park MC, Cadet ER, Levine WN, Bigliani LU, Ahmad CS. Tendon-to-bone pressure distributions at a repaired rotator cuff footprint using transosseous suture and suture anchor fixation techniques. Am J Sports Med 2005;33:1154-9.
22. Park MC, Elattrache NS, Ahmad CS, Tibone JE. "Transosseous-equivalent" rotator cuff repair technique. Arthroscopy 2006;22:1360e1-5.
23. Park MC, Elattrache NS, Tibone JE, Ahmad CS, Jun BJ, Lee TQ. Part I: Footprint contact characteristics for a transosseous-equivalent rotator cuff repair technique compared with a double-row technique. J Shoulder Elbow Surg 2007;16:461-8.
24. Park MC, Tibone JE, Elattrache NS, Ahmad CS, Jun BJ, Lee TQ. Part II: Biomechanical assessment for a footprint-restoring transosseous-equivalent rotator cuff repair technique compared with a double-row repair technique. J Shoulder Elbow Surg 2007;16:469-76.
25. Petit CJ, Boswell R, Mahar A, Tasto J, Pedowitz RA. Biomechanical evaluation of a new technique for rotator cuff repair. Am J Sports Med 2003;31:849-53.
26. Sano H, Wakabayashi I, Itoi E. Stress distribution in the supraspinatus tendon with partial-thickness tears: An analysis using two-dimensional finite element model. J Shoulder Elbow Surg 2006;15:100-5.
27. Sano H, Yamashita T, Wakabayashi I, Itoi E. Stress distribution in the supraspinatus tendon after tendon repair: Suture anchors versus transosseous suture fixation. Am J Sports Med 2007;35:542-6.
28. Tingart MJ, Apreleva M, Lehtinen J, Zurakowski D, Warner JJ. Anchor design and bone mineral density affect the pull-out strength of suture anchors in rotator cuff repair: which anchors are best to use in patients with low bone quality? Am J Sports Med 2004;32:1466-73.
29. Wakabayashi I, Itoi E, Sano H, Shibuya Y, Sashi R, Minagawa H, et al. Mechanical environment of the supraspinatus tendon: a two-dimensional finite element model analysis. J Shoulder Elbow Surg 2003;12:612-7.
30. Waltrip RL, Zheng N, Dugas JR, Andrews JR. Rotator cuff repair. A biomechanical comparison of three techniques. Am J Sports Med 2003;31:493-7.

〔症例報告〕

リウマチ肘の上腕骨遠位端関節内粉砕骨折に対し人工肘関節置換術を施行した2例

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索引用語：人工肘関節置換術，関節リウマチ，上腕骨遠位端関節内粉砕骨折

はじめに

関節リウマチ（以下RA）患者における上腕骨遠位端関節内骨折は観血的整復固定術が困難な場合がある．そこで上腕骨遠位端骨折の偽関節や高齢者の同骨折に対し，人工肘関節置換術（以下TEA）を行った報告が近年，散見される[1,2)]．われわれは，RA患者における上腕骨遠位端骨折の2例に，半拘束型TEAを施行し，良好な成績を得たので報告する．

症　例

症例1：64歳女性で，主訴は右肘の不安定性であった．既往歴として11年前よりRA（受診時Steinbrocker stage IV, class II）の診断にてブシラミン内服中であった．現病歴は，交通事故にて右上腕骨遠位端粉砕骨折（AO type C-3）を受傷した（**図1**）．前医にて観血的整復固定術施行されたが，術後2ヵ月時に，プレート部に繋がる皮膚瘻孔の形成および創感染を認めた．スクリュー・プレートの抜去，顆上部遠位骨片の摘出が施行された．その後より肘の動揺性を認めるようになった．受傷後4ヵ月で，手術目的に当科を受診した．初診時，右肘は著しく変形し，食事，洗顔，結髪動作困難であった．肘関節自動可動域は屈曲80°，伸展−20°，回内0°，回外90°で，全方向に強い動揺性を認めた．筋力はMMTでbiceps 4，triceps 4，握力12 kgであった．尺骨神経などの神経麻痺症状は認めなかった．術前JOA scoreは52点，Mayo elbow scoreは65点，DASH scoreは58.3点であった．術前血液検査所見では，炎症反応は認めなかった（CRP 0.34, ESR（1 h）17,（2 h）34）．抜釘時および当科での肘関節穿刺による細菌培養検査は一般細菌，嫌気性菌ともに陰性であった．

初診時単純X線像およびCT像では上腕骨は腕尺，腕橈関節より脱臼し，外側へ転位，上腕骨遠位部は肘頭窩上縁より欠損していた（**図2**）．肘機能改善を目的として半拘束型TEA（Coonrad-Morrey type）を受傷後7ヵ月で施行した．周囲の筋，軟部組織の短縮が著しく，残存した上腕骨遠位を4 cm切除し上腕骨コンポーネントを挿入した．近位橈尺関節の変形は術前，術中とも認めず，コンポーネント挿入後，回旋制限は改善したため，橈骨頭は温存した．切除した骨は上腕骨コンポーネントの前方フランジへ骨移植として用いた（**図3**）．術後経過は良好で，術後1週間のギプス固定の後，介助下関節可動域訓練を行い，術後

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Key words: total elbow arthroplasty, rheumatoid arthritis, humerus fracture

受傷時右肘単純X線像　初回骨折手術後右肘単純X線像　金属抜去時右肘単純X線像

図1　症例1
上腕骨顆上部の骨片は摘出されている．

図2　症例1：TEA前右肘単純X線像

4週より装具装着下での自動的関節可動域訓練とし，術後2ヵ月で活動制限を解除した．術後1年現在，肘関節痛は認めず，洗顔動作や結髪動作は可能で，日常生活動作は著しく改善した（**図4**）．肘関節の可動域は屈曲120°，伸展0°，回内75°，回外80°と増大した．上肢長は右44.5 cm，左47 cmと短縮認めるものの，JOA scoreは91点，Mayo elbow scoreは100点，DASH scoreは30点と改善し，患者満足度は非常に高い．

症例2：54歳女性，20年来RA（受診時Steinbrocker stage IV，class III）にてメトトレキサート，ブシラミン内服中であった．左肘はTEAをすでに施行されており，右側もTEAを予定されていたところ，通院の帰りに転倒し，右上腕骨遠位端骨折（AO type C-1）を受傷した．

骨折受傷前の右肘は，関節可動域は屈曲140°，伸展−40°で，食事は右手を使用せず，結髪動作は不能で，洗顔と結帯動作は困難であった．JOA scoreは47点，Mayo elbow scoreは55点，DASH scoreは67点であった．

単純X線像は，受傷前はLarsen分類grade Vであったが，受傷後はAO type C-1の骨折を認め，内側の骨片は大きく転位していた（**図5**）．CTにおいても同様の骨片の転位を認めた．受傷後2週で半拘束型TEA（Coonrad-Morrey type）を施行した．受傷前より橈骨頭は変形していたため，橈骨頭は切除した（**図6**）．術後経過は良好で，術後1年6ヵ月現在，肘関節痛は認めず，ADLも著し

図 3　症例1：TEA前右肘CT
橈骨，尺骨は近位へ転位し，顆上部は欠損している．

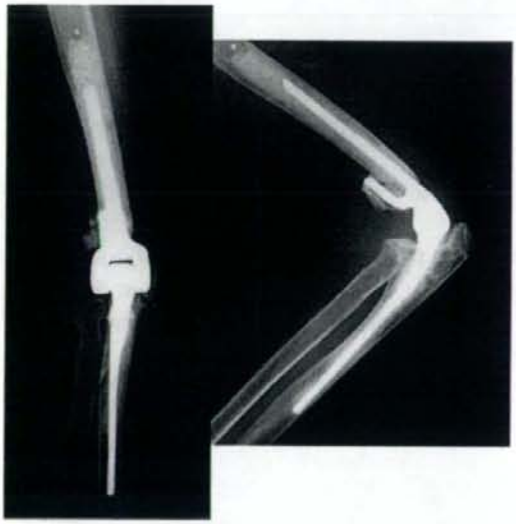

図 4　症例1：TEA後1年右肘単純X線像

図 5　症例2：受傷時右肘単純X線像

く改善した．肘関節可動域は屈曲125°，伸展－35°，回内80°，回外75°で，JOA scoreは94点，Mayo elbow scoreは95点と良好な結果であった．

考　察

RA患者や高齢者の上腕骨遠位端骨折において，骨粗鬆症による骨の脆弱性，偽関節発生の可能性に対する危惧や，長期固定による関節可動域制限などの合併症の問題から，早期の半拘束型TEAを推奨する意見がある．Cobbら[1]は，RA患者を含む，平均72歳の高齢者の新鮮骨折21例にTEAを施行して，良好な成績を報告している．またFrankleら[2]は，65歳以上の新鮮骨折患者24例を，骨接合術を行った群12例と半拘束型TEAを行った群12例の2群に分け，結果を比較検討した．骨接合術群ではexcellent 4例，good 4例，fair 1例，poor 3例であったのに対し，TEA群ではexcellent 11例，good 1例であった．この結果からRAや骨粗鬆症例には骨接合術よりTEAを推奨している．

今回のわれわれの症例は，RA患者で，骨折部

図 6　症例2：TEA 術直後右肘単純X線像

の骨・関節破壊が著しかったことから半拘束型TEA を実施した．術前より著しい日常生活動作の制限があったため，術後成績に対する患者の満足度は非常に高い．

Schneeberger ら[3]は一般的な上腕骨遠位端骨折に対して半拘束型 TEA を行う場合，活動性の高い患者や術後プロトコールを守れない患者は相対的禁忌であると述べている．本症例は，RA 患者であり，なおかつ比較的活動性の高い患者であることから，長期にわたって loosening の発生につき経過観察を行う必要があると考えている．

ま と め

1．RA 患者における上腕骨遠位端関節内粉砕骨折の 2 例に半拘束型人工肘関節置換術を施行し，良好な成績を得た．

2．RA 患者の上腕骨遠位端関節内粉砕骨折には，半拘束型人工肘関節置換術は有効な治療法であった．

文　献

1) Cobb TK and Morrey BF: Total elbow arthroplasty as primary treatment for distal humeral fractures in elderly patients. J Bone Joint Surg Am 77: 826-832, 1997.
2) Frankle MA, et al: A comparison of open reduction and internal fixation and primary total elbow arthroplasty in the treatment of intraarticular distal humerus fractures in women older than age 65. J Orthop Trauma 17: 473-480, 2003.
3) Schneeberger AG, et al: Semiconstrained total elbow replacement for the treatment of post-traumatic osteoarthrosis. J Bone Joint Surg Am 79: 1211-1222, 1997.

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ORIGINAL ARTICLE

Tailor-made surgical guide based on rapid prototyping technique for cup insertion in total hip arthroplasty

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Abstract

Background A surgical guide made by the rapid prototyping (RP) technique for cup insertion in total hip arthroplasty might be useful to avoid malalignment of the cup, which indicates postoperative complications.

Methods To address this research question, we applied a RP-based guide to 24 patients with their CT images. We designed it to fit onto the acetabular edge and to insert a Kirschner wire (K-wire) which indicated a planned cup direction. We intraoperatively placed it on the acetabular edge, inserted the K-wire through the guide on the superior acetabulum and implanted the cup while observing the alignment of the K-wire. We also recorded the additional time needed to use the guide.

Results The mean cup accuracy between planned and postoperative alignments was 2.8° (SD = 2.1°) for abduction and 3.7° (SD = 2.7°) for anteversion. The mean additional time was 3.5 (range 2–6) min.

Conclusion We can use this guide with acceptable accuracy and without consuming an excessive amount of time. Copyright © 2009 John Wiley & Sons, Ltd.

Keywords surgical guide; total hip arthroplasty; rapid prototyping technique; tailor-made

Introduction

In total hip arthroplasty (THA), fixation of the acetabular component (cup) requires optimal alignment, which is defined as a 'safe zone' by one author (1), in order to reduce postoperative complications, such as cup–neck impingement and hip dislocation. The zone is an abduction angle of 40 ± 10° and an anteversion angle of 15 ± 10°. With this range the dislocation rate was 1.5% and outside this range it was 6.1%. Because 22–71% of cases with the conventional manual procedure are achieved within the safe zone (2–5), some computer navigation systems with optical sensors have been used to reduce angle variations of the cup (4–7). However, this kind of system has a high cost per arthroplasty case (an additional $600–2000 for navigation) (8) and involves intraoperatively time-consuming procedures (an additional 15–46 min of operating time compared with conventional procedures) (8,9).

Another computer-assisted surgery technique that involves few time-consuming intraoperative procedures is the use of a tailor-made surgical guide, made using the rapid prototyping (RP) technique, which