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Arthroscopic Suture Bridge Fixation Technique with Multiple Crossover Ties for Posterior Cruciate Ligament Tibial Avulsion Fracture

Jung-Ro Yoon[1], Chan-Deok Park[2], Dae-Hee Lee[2]

Abstract

Purpose: This study examined the clinical outcomes of a newly developed technique, arthroscopic suture bridge fixation with crossover ties of PCL tibial avulsion fracture using two tibial tunnels and a posterior trans-septal portal.

Methods: Records were reviewed of 18 patients (median age 33.5 years, range 13–55 years) with PCL tibial avulsion fractures treated with an arthroscopic suture bridge technique. Knee function before surgery and at last follow-up was evaluated by Lysholm and Tegner scores. A KT-2000 arthrometer was used to evaluate knee stability, and fracture union was assessed by plain radiographs.

Results: Mean postoperative Lysholm ($P < 0.001$) and Tegner ($P = 0.011$) scores showed significant improvements compared with preoperative scores. Arthrometry showed that the mean side-to-side difference improved significantly, from 7.8 ± 0.8 mm preoperatively to 3 ± 1.2 mm postoperatively ($P = 0.012$). Radiographic evaluation showed solid union at the fracture site in all 18 patients at last follow-up.

Conclusion: This new arthroscopic double-tunnel pull-out suture bridge fixation with multiple crossover ties and posterior trans-septal technique for PCL tibial avulsion fracture yielded good clinico-radiological outcomes, including satisfactory stability and fracture site healing. This technique can be a useful treatment option for PCL tibial avulsion fracture even with small

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comminuted fracture due to compression by the unique crossover configuration mesh of multiple fixation sutures.
Level of evidence: IV.

Keywords Posterior cruciate ligament, Avulsion, Arthroscopy, Pull-out suture

Introduction

Largely displaced avulsed fractures of the posterior cruciate ligament (PCL) tibial attachment site have traditionally been treated with open reduction and internal fixation with a cannulated screw [1, 5]. Reliable fixation with screws, however, may not be achieved if the PCL avulsion fracture fragment is very small and too severely comminuted, indicating a need for suture fixation [11, 17]. As arthroscopic skills and instruments have improved, surgical treatment of PCL avulsion fractures on the tibial side has shifted from an open to an arthroscopic approach [7–9]. Biomechanical studies have shown that maximal load and stiffness did not differ significantly between patients who underwent suture fixation and screw fixation for PCL tibial avulsion fractures [4, 14]. Arthroscopic suture-based fixation is more versatile than screw fixation, increasing its use in patients with PCL tibial avulsion fractures. Arthroscopic suture-based fixation methods can be classified according to the number of portals and tibial tunnels for suture passage and fixation [20, 21]. To date, however, no arthroscopic suture fixation technique has utilized a suture configuration that surrounds not only the PCL substance but also the avulsed fragment. In the present work, a new technique was therefore developed, involving arthroscopic crossover tie suture bridge fixation of PCL tibial avulsion fractures using two tibial tunnels and a posterior trans-septal portal. This study reports the clinical outcomes of this technique in patients with PCL tibial avulsion fractures. It was hypothesized that this method would achieve reliable clinico-radiological outcomes in these patients.

Materials and Methods

Inclusion Criteria and Enrolled Patients

Patients were included if they had undergone arthroscopic suture bridge fixation with the crossover tie technique for PCL avulsion fractures. Indications for suture bridge fixation included isolated PCL tibial avulsion fractures with >3-mm displacement, with or without comminution. Patients were excluded if displacement was minimal (<3 mm) or if they had an associated tibial plateau fracture or other ligament tear that needed surgical treatment. All PCL tibial avulsion fractures were confirmed by radiography, computed tomography (CT) scanning and/or magnetic resonance imaging (MRI, Fig. 1a). The size, comminution, and displacement amount of avulsed fragments were assessed by three-dimensional CT scans (Fig. 1b). MRI was performed in patients

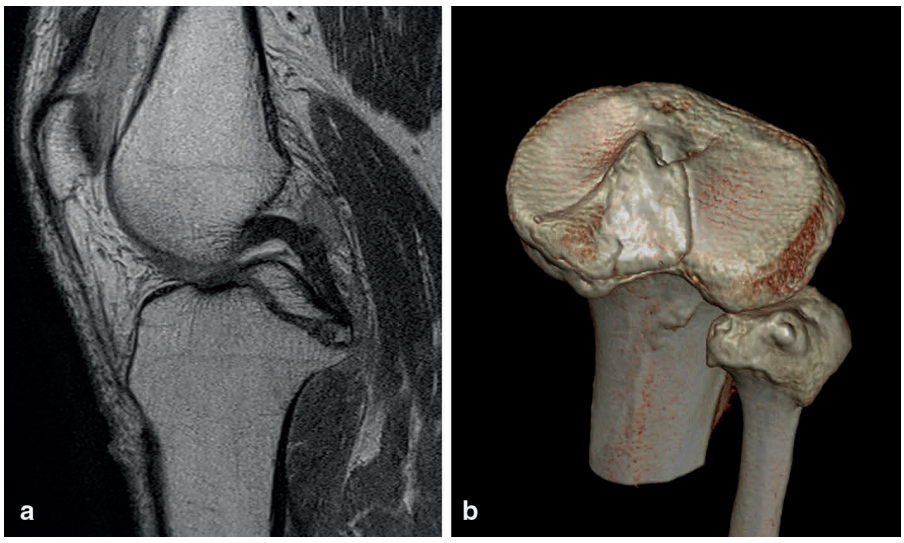

Fig. 1: Evaluation of the displacement and configuration of an avulsion fracture fragment of the posterior cruciate ligament tibial attachment by **a** magnetic resonance imaging and **b** computed tomography scanning.

with a suspected associated ligament injury and in children with a suspected osteochondral fracture, because CT scans could not reveal cartilaginous fragments.

From 2010 to 2014, 20 patients with PCL tibial avulsion fractures were treated with arthroscopic suture bridge fixation with crossover tie. As two of these patients were lost to follow-up, the medical records and radiographs of the remaining 18 knees of 18 patients were retrospectively reviewed. The study was approved by the Ethics Committee of our institution. Patients who had undergone arthroscopic suture bridge fixation for PCL tibial avulsion fracture using the multiple crossover ties technique retrospectively consented by telephone to involvement in the study. Table 1 shows detailed anthropometric data of patients.

Surgical Technique (video)

Creation of a Posterior Trans-septal Portal

Surgery began by constructing transseptal portals using trans-illumination. The anterolateral (AL) and anteromedial (AM) portals were constructed initially, followed by the posteromedial (PM) and posterolateral (PL) portals. The arthroscope was inserted through the PM portal, allowing views of the PCL remnant and the posterior septum. A switching stick was inserted via the PL portal to push the septum medially. A motorized shaver was inserted through the AM portal, reaching the PM compartment through an intercondylar notch. This shaver was used to

Table 1: Summary of anthropometric patient characteristics.

Parameter	
Numbers of male:female patients	12:6
Age (years)[a]	33.5 (13–55)
Height (cm)[b]	162.3 (150–181)
Weight (kg)[b]	64.7 (50–85)
Body mass index (kg/m^2)[b]	24.4 (21.4–26.9)
Interval from injury to surgery[b] (day)	6.4 ± 5.9 (2–21)

[a]Median (range)
[b]Mean ± standard deviation (range)

excise step-by-step the medial wall of the posterior septum, along with fatty tissues behind the PCL remnant. The posterior trans-septal portal was generated in the central part of the posterior septum, behind the PCL.

Sewing the PCL Using a Suture Hook

A crescent-shaped suture hook loaded with a No. 1 polydioxanone (PDS) suture (used as a fixation suture) was introduced through the posterolateral portal and advanced through the PCL substance just above the avulsed fragment, from the lateral border to the medial border of the PCL (Fig. 2a). One end of the PDS suture was retrieved through the anteromedial portal using a suture retriever, whereas the opposite end was left at the posterolateral portal. This procedure was repeated three or four times, as necessary, depending on the size of the avulsed bony fragment and the extent of comminution.

Double Tibial Tunnel Preparation

While maintaining the arthroscope at the PM portal, a motorized shaver was inserted through the PL portal, passing through the orifice of the posterior septum to reach the PCL tibial insertion site. The posterior capsule was debrided such that the margin of the crater of the avulsed fracture fragment could be visualized. A tibial tunnel was created at the medial border of the PCL tibial attachment site or the medial margin of the crater, from which the avulsed bony fragment was peeled off (Fig. 2b). In generating the tibial tunnel at the medial border of the PCL tibial attachment site, the tip of the PCL tibial drill guide was inserted through the AM portal at an angle of 45°–50°. The drill guide was subsequently advanced through the space between the PCL and the medial femoral condyle. The extraarticular portion of the tibia drill guide was placed in contact with the AM surface of the proximal tibia. After inserting a 2.0-mm guide pin into the PCL tibial attachment site, the tibial tunnel was created with a 4.5-mm cannulated reamer. The retraction suture for shuttle relay of PDS fixation sutures was introduced into the cannulated reamer from the anteromedial cortex of the proximal tibia (Fig. 2c). A suture retriever inserted through the

posterolateral portal was used to extract one end of the retraction suture that passed through the inside of the cannulated reamer and reached the posterior cortex of the proximal tibia. The ends of three or four PDS fixation sutures and of one retraction suture should be simultaneously held and extracted through the posterolateral portal using a suture retriever, ensuring that all the suture ends were in the same soft-tissue passage in the posterolateral portal. This prevented possible snagging of soft tissue if the knot for shuttle relay was pushed back into the joint. Outside the posterolateral portal, the PDS fixation sutures were tied with the retraction suture, and the retraction suture was pulled out of the tibial tunnel, enabling the PDS fixation sutures to follow the retraction suture and to be extracted from inside the tibial tunnel. This procedure resulted in the PDS fixation sutures crossing the PCL at the tibial attachment site (Fig. 2d).

To create a tibial tunnel at the lateral border of the PCL tibial attachment site (Fig. 2e), the PCL tibial drill guide was advanced through the space between the ACL and the PCL [16]. A 2.0-mm guidewire was over drilled with a 4.5-mm cannulated reamer. Similar to the method used to construct the tibial tunnel at the medial border of PCL, the retraction suture was introduced into the cannulated reamer. The suture retriever was inserted via the anteromedial portal and advanced to the posterior compartment, resulting in one end of the retraction suture being located at the

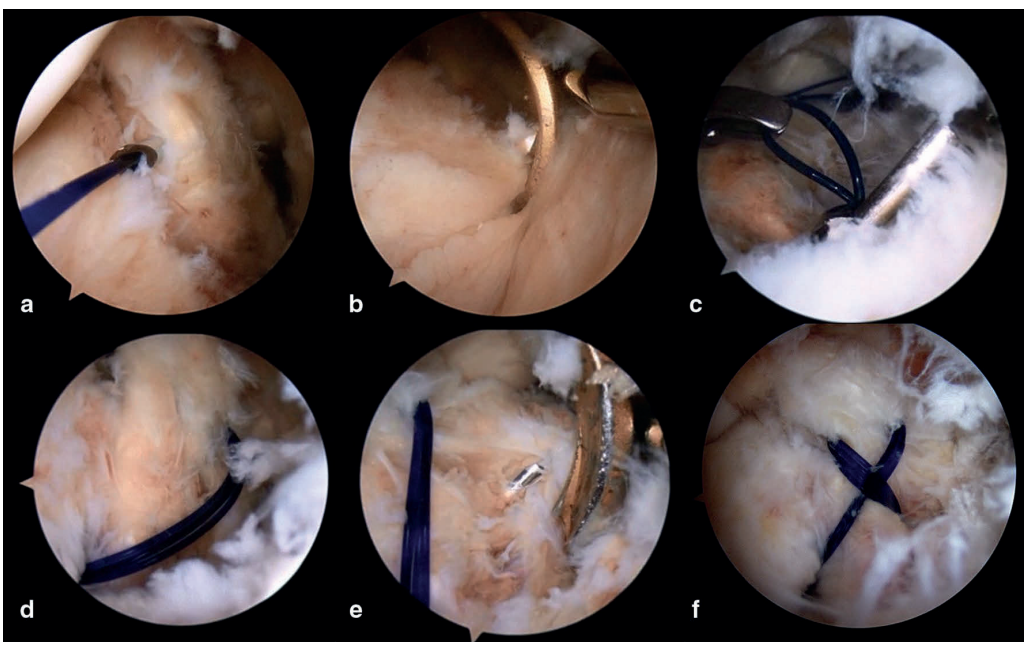

Fig. 2: Arthroscopic suture bridge fixation technique. **a** Piercing of the posterior cruciate ligament (PCL) with a suture hook loaded with a polydioxanone (PDS) suture and used as a fixation suture. **b** Creation of the tibial tunnel at the medial margin of the crater. **c** Introduction of the retraction suture for shuttle relay of the PDS fixation sutures into the cannulated reamer from the anteromedial cortex of the proximal tibia. **d** Removal of the retraction suture from the tibial tunnel, enabling the PDS fixation sutures to cross over the PCL at the tibial attachment site. **e** Creation of another tibial tunnel at the lateral border of the PCL tibial attachment site, by advancing the guide pin along the PCL tibial drill guide. **f** Wrapping of the PCL with the bundle of PDS fixation sutures in a crossover tie configuration.

anteromedial portal. After simultaneous extraction of all ends of PDS fixation sutures and one end of the retraction suture, the former were tied with a retraction suture outside the anteromedial portal. The retraction sutures were pulled out of the tibial tunnel, along with the PDS fixation suture ends located at the anteromedial portal. Finally, the two ends of the suture were tightened to achieve reduction, which was adjusted using probes, and tied over the tibial cortex between the two outer openings of the tunnels. The bundle of PDS fixation sutures therefore wrapped the PCL, compressing the avulsed fragment in the shape of a crossover tie (Fig. 2f).

Clinico-radiological Evaluation

Knee function was evaluated by the Lysholm scoring system and Tegner activity scale. Patients were also evaluated according to the International Knee Documentation Committee (IKDC) knee ligament examination form, on which knees were graded as normal (grade A), nearly normal (grade B), abnormal (grade C), or severely abnormal (grade D). A KT-2000 arthrometer was used to evaluate knee stability, range of motion (ROM), and side-to-side differences. All patients underwent anteroposterior and lateral radiography of the knee immediately after surgery and 3, 6, 12, and 24 months postoperatively. The union of fracture was judged by visualization of fracture line and stability. Fractures were regarded as united if the fracture line was invisible and/or the patients had no evidence of clinical instability. All parameters were measured by 2 orthopaedic surgeons with significant experience. These measurements were again taken 2 weeks later. The ethical approval of this study protocol was granted by Institutional Review Board of the Samsung Medical Center (permit no. 2014-12-166).

Statistical Analysis

Paired Student's t tests were used to compare pre- and postoperative Lysholm and Tegner scores, and the mean side-to-side difference on KT-2000 examination. All statistical analyses were performed using SPSS software version 12 (SPSS Inc., Chicago, IL, USA). A P value of <0.05 was considered statistically significant. The reliabilities of measurements of instability (KT-2000) and radiographic healing of fracture site were determined by calculating the intraclass correlation coefficient (ICC), which quantifies the proportion of differences due to measurement variability. The ICC can range from 0 to 1, with greater than 0.75 representing good agreement and less than 0.40 representing poor agreement. At an α level of 0.05 and a power of 0.8, we performed a post hoc power analysis to detect a mean difference of 4 mm for side to side difference of KT 2000 from before to after surgery. This study included 18 patients, with adequate power, to detect significant differences in side to side difference (0.818) from before to after surgery.

Results

In this study, interobserver reliability ranged from 0.752 to 0.857 and intraobserver reliability ranged from 0.758 to 0.841, indicating good reliability for instability test using KT-2000 and

assessment of fracture healing on postoperative radiograph. The present study included 18 patients, 12 males and 6 females, of mean age 32.4 years (range 13–55 years). PCL injuries were due to traffic accidents in 12 patients, sports injuries in four, and falls in two. All patients were followed up for a mean of 26 months (range 22–30 months). Mean Lysholm score in the 18 patients was significantly higher postoperatively than preoperatively (90 ± 5 vs. 40 ± 10, $P < 0.001$). The IKDC grade was A (normal) in ten patients (56 %), B (nearly normal) in seven (39 %), and C (abnormal) in one (5 %). Median Tegner score also showed a significant improvement after than before surgery (7.4, range 5–9 vs. 3.5, range 2–5, $P = 0.011$). The range of motion, which was 0° preoperatively, improved to 140.0 ± 5.6° at last follow-up. KT-2000 examination showed that the median side-to-side difference was significantly smaller at last follow-up than preoperatively (3.2, range 2.4–3.8 mm vs. 7.8, range 5.5–8.9 mm, $P = 0.012$). Radiographic evaluation at last follow-up showed solid union at the fracture site in all 18 patients. None of the patients experienced a major complication, including neurovascular injuries or perioperative wound infection.

Discussion

The most important finding of the present study was to introduce a newly developed arthroscopic surgical technique for PCL tibial avulsion fractures, using a double tibial tunnel, multiple crossover ties, suture bridge fixation, and posterior transseptal formation. This new method showed good clinico-radiological results, with no complications.

Arthroscopic suture fixation techniques can be classified by types of portals and suture material, and by the number of tibial tunnels for suture passage and fixation [2, 3, 7–9]. The method described here uses a posterior trans-septal portal connected to the posteromedial and posterolateral portals [10, 15]. Most other techniques use one or two posteromedial portals for visualization and an instrument entrance for the procedure [2, 13]. One posteromedial portal technique is unable to visualize the posterior compartment around the PCL tibial insertion site, the location of the most important and dangerous procedure of guide pin insertion for tibial tunnel reaming. Another method uses the posteromedial portal mainly as a working portal for insertion of instruments such as a grasper or for suture retrieval. Visualization of the operation site requires a trans-notch view, using a 70° arthroscopic camera passed from the anteromedial portal to the posterior compartment. However, the visual field provided by the trans-notch view is not as wide as that provided by the posterior trans-septal portal. Use of two posteromedial portals, both low and high, could not completely resolve the problem of a narrow visual field, despite the high posteromedial portal being used as a viewing portal. This portal was unable to visualize the lateral margin of the PCL tibial attachment site, in which the tibial tunnel was created using a two tunnel technique, because the posterior septum located between the PCL posterior margin and posterior capsule could obstruct the lateral margin of the PCL tibial attachment. Another drawback of the two posteromedial portal technique is crowding of instruments, including the arthroscopic camera and surgical device, due to the narrow space of the posteromedial compartment. As these problems could be solved using a posterior trans-septal portal, this approach was used routinely for suture bridge fixation of PCL avulsion fractures.

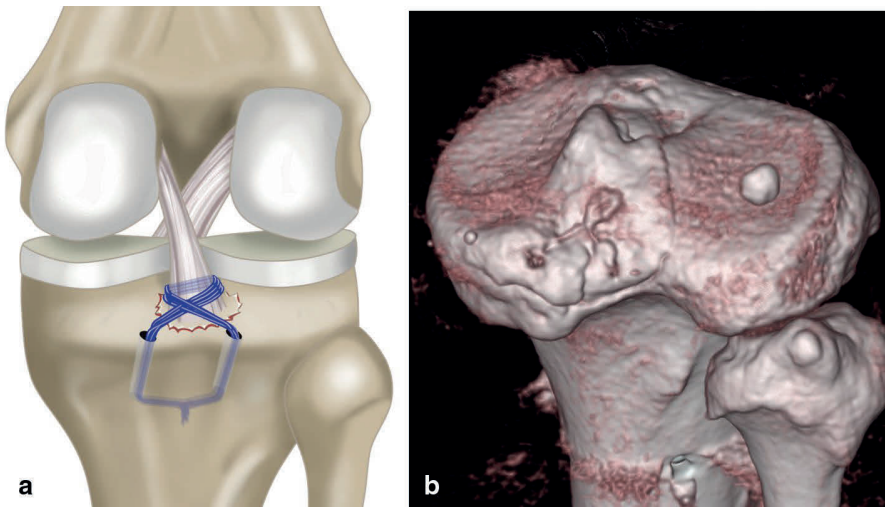

Fig. 3: a Schematic diagram and **b** a postoperative 3D computed tomography scan of the crossover tie configuration of multiple sutures piercing the posterior cruciate ligament (PCL).

Most techniques involve the creation of one or two tibial tunnels for suture passage and fixation. The single-tunnel technique requires an additional method to fix the ends of the sutures, such as using post-ties with washers and screws. Tightening these screws may result in excessive twisting of the knots and thread snapping. In addition, removal of these washers and screws requires additional surgery. In contrast, the double-tunnel technique requires no further surgery for implant removal, because this technique requires only that the ends of the sutures be knotted and therefore does not require additional fixation devices. These reasons prompted the creation of double tibial tunnels for suture passage and fixation.

Choice of suture material must also be considered when performing suture-based fixation of PCL tibial avulsion fractures. Other suture-based fixation techniques have used polydioxanone (PDS) and polyester sutures. As long as the PDS is not damaged, sutures made of this material have equivalent or higher strength than nonabsorbable sutures such as those made of polyester [6]. Furthermore, more than 50 % of the original strength of PDS sutures remains at 6 weeks post-implantation, at which time PCL avulsion fractures have partially healed [18]. Our choice of PDS sutures for fixation was based not only on the higher mechanical strength of PDS but on it being absorbable, with minimal foreign body reaction and a reduced possibility of infection. In addition, absorbable sutures should be used to treat osteochondral PCL avulsion fractures in children, to minimize injury to the growth plate.

The pull-out suture bridge fixation technique of the current study had several advantages compared with previous methods. Three or four PDS sutures were sewn into the PCL tibial attachment base by a suture hook penetrating the PCL substance rather than the avulsed bone. These sutures constitute a mesh, which could indirectly reduce avulsed bony fragments even

in small comminuted fractures such as chondral fractures in paediatric patients [9, 12, 19]. Additionally, both suture ends that penetrated the PCL base cross over each other in an "X" shape (Fig. 3a, b). This crossover configuration of multiple fixation sutures enabled proper reduction and compression of elevated avulsed bony fragments.

This study had several limitations, including the small patient population and the lack of comparison with other treatment modalities such as screw fixation. However, the incidence of PCL tibial avulsion fractures is relatively low. Furthermore, surgeons may prefer the surgical method, because screw fixation is regarded as adequate for large bony fragments without comminution and suture fixation is regarded as appropriate for small fragments with comminution. Therefore, from a practical standpoint it is difficult to design and perform randomized controlled trials comparing suture and screw fixation for PCL tibial avulsion fractures.

Conclusions

In conclusion, arthroscopic double-tunnel pull-out suture bridge fixation with multiple crossover ties and posterior trans-septal technique yielded good clinico-radiological outcomes in patients with PCL tibial avulsion fractures, including satisfactory stability and fracture site healing.

Compliance with ethical standards

Conflict of interest: The authors report that no conflicts of interest have occurred that are associated with the current study.

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Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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The Effect of Concomitant Coracohumeral Ligament Release in Arthroscopic Rotator Cuff Repair to Prevent Postoperative Stiffness: A Retrospective Comparative Study

Joo Hyun Park[1], Seok Hoon Yang[2], Sung Min Rhee[1], Joo Han Oh[1]

Abstract

Purpose: This study was to evaluate the efficacy and safety of coracohumeral ligament (CHL) release from the coracoid process concomitant with arthroscopic rotator cuff repair for preventing postoperative stiffness.

Methods: Data on patients who underwent arthroscopic rotator cuff repair with a minimum follow-up of 1 year were collected retrospectively. Propensity score matching (1-to-1) was performed between a no-releasing group (Group I) and CHL-releasing group (Group II). In total, 76 patients in each group were matched. Clinical outcomes were assessed and compared between the two groups, including range of motion (ROM) and visual analogue scale for pain (pVAS) at postoperative 3 months, 6 months, and 1 year. The integrity of the repaired tendon was assessed at 1-year follow-up using either magnetic resonance imaging or ultrasonography.

Results: External rotation (ER) at side at postoperative 3 months in Group II was better than that in Group I (48.6° ± 11.6° vs. 38.4° ± 13.0°, $P < 0.001$). When evaluating only patients with a small-to-medium sized tear at postoperative 3 months, ER at side was 49.8° ± 10.9° in Group II

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versus 37.8° ± 13.1° in Group I ($P < 0.001$). In patients with a large-to-massive sized tear, however, there was no significant difference in ER at side at postoperative 3 months (n.s.). There was no significant difference in ROM and functional scores at postoperative 6 months and 1 year, and there was no significant difference in healing failure rate (6 cases in Group I (7.9%), 2 cases in Group II (2.6%); n.s.). No complications of the CHL release procedure occurred.
Conclusions: In arthroscopic rotator cuff repair, CHL release from the coracoid process without creating a rotator interval defect could be an effective and safe method to prevent early postoperative stiffness, especially ER at side in patients with a small-to-medium sized tear. Therefore, CHL release can be used as a selective procedure to prevent postoperative stiffness in patients that may benefit from this procedure with decreased preoperative ER compared to the normal side.
Level of evidence: Level III.

Keywords Rotator cuff tear, Rotator cuff repair, Coracohumeral ligament, Coracoid process, Range of motion

Introduction

Arthroscopic rotator cuff repair is generally regarded as the first-line treatment for symptomatic full-thickness rotator cuff tears. Arthroscopic repair has several advantages over open repair, including less injury to the deltoid muscle, reduced morbidity, and lower risk of postoperative stiffness [5, 10, 33, 34]. However, postoperative stiffness remains one of the most common complications after arthroscopic rotator cuff repair [3, 4, 14]. The prediction and prevention of shoulder stiffness is particularly important in the early postoperative period, which can lead to uncomfortable pain and adverse effects leading to obstacles during scheduled rehabilitation [8, 20, 27, 28]. Shoulder stiffness arises from capsular contracture, adhesion, or scarring of the surrounding soft tissues [7, 27]. It can cause severe pain and limited range of motion (ROM), making it difficult to rehabilitate patients and decreasing functional outcomes [4, 11, 14]. Surgeons have made several efforts to minimize postoperative stiffness, for instance, encouraging vigorous early passive shoulder exercise [8, 20], injecting an anti-adhesive agent into the glenohumeral or subacromial space postoperatively [27], or the combination of rotator cuff repair with either manipulation under anesthesia or arthroscopic capsular release [6, 13, 18, 28]. Despite these attempts, there is a lack of consensus on the most effective surgical procedure to prevent postoperative stiffness during arthroscopic rotator cuff repair.

Common magnetic resonance imaging (MRI) findings of shoulder stiffness have been reported to include thickening of the coracohumeral ligament (CHL) and joint capsule in the rotator cuff interval or obliteration of the fat triangle between the coracoid process and the CHL [23, 35]. Neer *et al*. reported that external rotation (ER) could be increased up to average of 32° on sectioning CHL only [25]. Although thickening of the CHL that covers the rotator interval is recognized as a causative factor limiting ER of the shoulder joint [15, 16, 25, 26], these pathologic

findings, especially from the base of the coracoid process to the superomedial capsule, could also restrict internal rotation (IR), such as hand behind back and horizontal flexion [19]. Therefore, CHL thickening, the major histologic factor of stiffness, should be resolved intraoperatively to maximize postoperative ROM. The purpose of this study was to evaluate the efficacy and safety of CHL release from the coracoid process concomitant with arthroscopic rotator cuff repair for preventing postoperative stiffness.

Materials and Methods

Inclusion and Exclusion Criteria

Between January 2014 and January 2016, 786 consecutive patients underwent arthroscopic rotator cuff repair at the senior author's institution. We enrolled patients who met the following inclusion criteria: patients with a high-grade partial thickness or full-thickness rotator cuff tear as verified by preoperative MRI, patients who underwent complete rotator cuff repair, and those who were followed-up for at least 1 year with evaluation of successful repair using ultrasound or MRI. Patients were also divided into two groups: arthroscopic rotator cuff repair without CHL release, from January 2014 to August 2014 (Group I) and arthroscopic rotator cuff repair with concomitant routine CHL release from the coracoid process, from September 2014 to January 2016 (Group II). Exclusion criteria for decreasing preoperative bias were as follows: patients who had preoperative shoulder stiffness ($n = 252$), patients undergoing revision surgery ($n = 9$), and those undergoing coracoplasty which has been done related to dynamic subcoracoid impingement [29] ($n = 49$). We defined shoulder stiffness as follows: passive forward flexion less than 120°, passive ER with the arm at the side less than 30°, and passive IR at the back lower than L3, as previously described [7, 28]. Patients who met one of these three criteria were considered to have preoperative stiffness. Before propensity score matching, there were 150 patients in Group I and 326 patients in Group II, respectively. All variables were successfully matched after propensity score matching, and a total of 76 patients in each group were enrolled in the final analysis (Fig. 1).

Surgical Procedure (video)

All arthroscopic procedures were performed by a single senior surgeon. After management of the pathologic lesion in the glenohumeral joint, subacromial decompression with bursectomy and acromioplasty were performed in all patients in the lateral decubitus position. In Group II, CHL was released from the undersurface of the coracoid process without violation of substantial tissue of the rotator interval (rotator interval release in-continuity) using a radiofrequency device through the lateral portal in the ER position, as the CHL in the externally rotated position becomes more tense as compared to the neutral position and can be more easily released (Fig. 2). Then, rotator cuff repair was performed through the single row or double row technique using suture anchors, according to tear size and tear configuration. In patients who also required

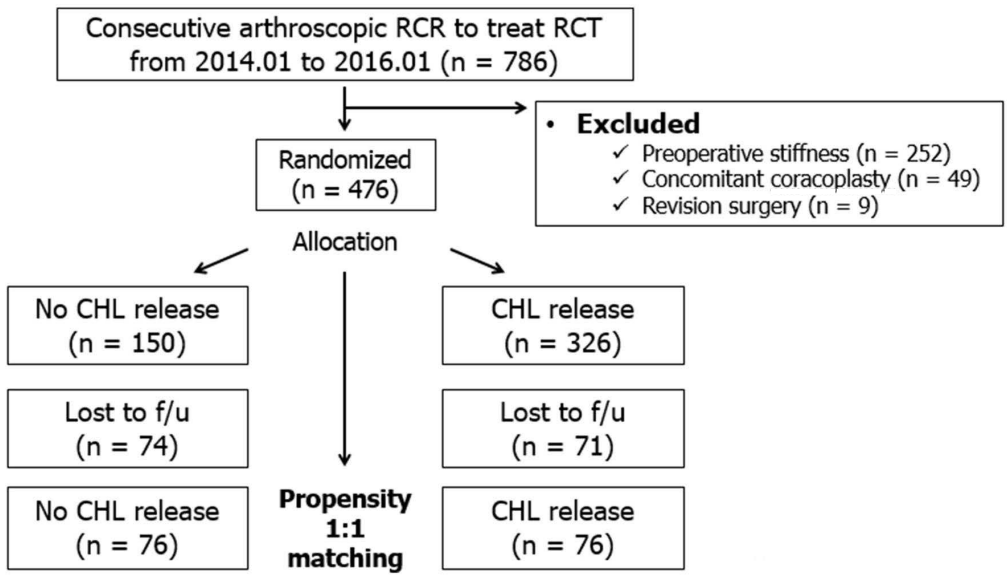
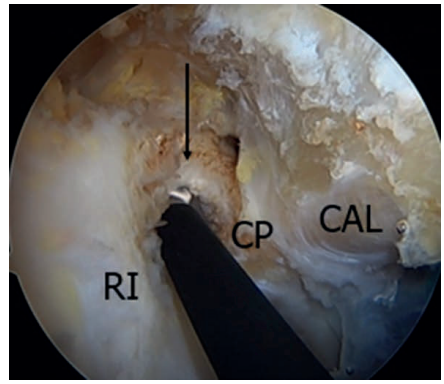


Fig. 1: Study design flow diagram. *RCR* rotator cuff repair, *RCT* rotator cuff tear, *CHL* coracohumeral ligament, *f/u* follow-up.

Fig. 2: The photo shows the subcoracoid space of the right shoulder of a 75-year-old patient who underwent arthroscopic rotator cuff repair in Group II. The coracohumeral ligament (black arrow) was released from the undersurface of the coracoid process without creating a rotator interval defect (rotator interval release in-continuity) using a radiofrequency device through the lateral portal. *RI* rotator interval, *CP* coracoid process, *CAL* coracoacromial ligament.



the subscapularis tendon repair, authors repaired subscapularis tendon in the subacromial space without opening a rotator interval with the suture anchor (triple-loaded) by single row technique. After the mobilization of subscapularis tendon and the preparation of lesser tuberosity were performed, the subscapularis tendon was repaired by simple sutures, and then rotator interval tissue was also repaired by one matrix suture with biceps tendon after tenotomy in the gleno-humeral joint. The immobilization with the abduction brace was applied for 4–6 weeks according to the tear size measured during surgery. Shrugging of the shoulder and active motion of the elbow (flexion, extension), forearm (supination, pronation), wrist, and hand were encouraged

immediately after surgery. After weaning from the brace, active assisted ROM was performed with a pre-established protocol. After full passive ROM was obtained, muscle-strengthening exercises were initiated, and all sports activities were permitted 6 months after surgery. All physical therapy protocols were performed with the cooperation and supervision of a rehabilitation physician.

Clinical Outcomes

Each patient was assessed by a clinical researcher, who was blinded to the current study, preoperatively and at 3 months, 6 months, and 1 year after surgery. The visual analog scale for pain (pVAS) was completed by all patients at each follow-up period, scaled from 0 to 10 (0, no pain; 10, the worst pain). Passive ROM (forward flexion, ER at side, IR at back) was measured using a goniometer with the scapular in a fixed position. IR at back was measured according to the vertebral level at which the tip of the thumb reached in the sitting position. The authors numbered the vertebrae serially as follows for convenience of analysis: 12 for the 12th thoracic vertebra, 13 for the 1st lumbar vertebra, and 17 for the 5th lumbar vertebra [7, 28]. The Constant score and the American Shoulder and Elbow Surgeons (ASES) score were also evaluated at 6 months and 1 year after surgery. Anatomic outcomes were evaluated using MRI or ultrasonography at least 1 year after surgery. All patients who underwent rotator cuff repair at the authors' institution were advised to undergo MRI for the evaluation of healing failure at 1 year postoperatively. For patients who refused MRI due to its high cost, we performed ultrasonography instead of MRI. A musculoskeletal radiologist with over 10 years of experience interpreted MRI and ultrasonography and determined the healing failure. Ultrasonography has been established as comparable with MRI for evaluating the repaired rotator cuff status [2]. And we also assessed during the follow-up period whether postoperative complications associated with CHL release, such as instability symptom, occurred. The study protocol was approved by the institutional review board of the senior author's hospital (SNUBH, B-1808/484-106).

Statistical Analysis

The Student's *t* test was used to compare pVAS, ROM, and functional scores between the two groups, and the paired t-test was used to compare these variables between two consecutive periods in each group. We used the Chi-square test to analyze categorical variables to compare patients' sex, dominant hand, and tear size. The level of statistical significance was set to $P < 0.05$. All statistical analyses were performed using IBM Statistical Package for the Social Sciences (SPSS) software version 19.0 (Chicago, IL, USA). A 1-to-1 matching was performed using the propensity scoring method, which can minimize selection bias. Co-variables included for matching were age, sex, dominant hand, number of involved tendons, and tear size of the torn tendon. Since there were no similar studies related to the CHL release to prevent postoperative stiffness, a power study for sample size calculation was not possible. However, the authors matched preoperative variables, including factors proven to affect postoperative stiffness, using propensity score methods and performed 1-to-1 matching for 76 among 476 patients to minimize selection bias.

Results

The mean age of all patients was 59.9 ± 9.2 years (range 35–79 years), and the mean overall follow-up period was 25.5 ± 11.6 months (range 12–48 months). The mean anteroposterior dimension of the tear was 16.7 ± 7.0 mm (range 5.0–35.0 mm) and mean retraction was 18.5 ± 8.5 mm (range 7.0–44.0 mm) (Table 1). There was no significant difference in patient age, sex, hand dominance, or tear size between the two groups, which were successfully matched by propensity score matching (Table 1). The average pVAS improved from 5.2 ± 2.0 points preoperatively to 0.7 ± 1.3 points

Table 1: Preoperative demographic data of the two groups after propensity score matching.

Variables	Group I (no-releasing) *n* = 76	Group II (CHL-releasing) *n* = 76	*P* value
Age (year)	59.7 ± 9.3	60.0 ± 9.2	n.s
Gender (M:F)	40:36	31:45	n.s
Dominant hand (dominant:non-dominant)	48:28	56:20	n.s
Tear size			
Retraction (mm)	19.8 ± 8.4	17.3 ± 8.5	n.s
AP (mm)	17.6 ± 6.9	15.7 ± 7.0	n.s
R1:R2:R3:R4 (n)	12:36:11:17	16:45:5:10	n.s
FF (°)	169.3 ± 8.5	167.6 ± 9.3	n.s
ER at side (°)	68.1 ± 16.7	69.5 ± 13.6	n.s
IR at back (level)	8.5 ± 2.1	7.9 ± 1.9	n.s

CHL coracohumeral ligament, *M* male, *F* female, *AP* antero-posterior, *R1* small-sized tear, *R2* medium-sized tear, *R3* large-sized tear, *R4* massive tear, *FF* forward flexion, *ER* external rotation, *IR* internal rotation (*1–12* thoracic vertebrae 1–12, *13–17* lumbar vertebrae 1–5, *18* sacrum)

Table 2: Clinical and functional outcomes of the two groups.

Variables	Period	Group I (no-releasing)	Group II (CHL-releasing)	*P* value
pVAS (point)	Preop	4.8 ± 2.0	5.1 ± 2.1	n.s
	POD 6M	1.1 ± 1.4	1.5 ± 1.7	n.s
	POD 1Y	0.8 ± 1.4	0.5 ± 1.1	n.s
Healed:healing failure (*n*)	POD 1Y	70:6	74:2	n.s
ASES score (point)	Preop	58.7 ± 16.1	59.6 ± 17.2	n.s
	POD 6M	89.4 ± 10.7	87.0 ± 12.5	n.s
	POD 1Y	91.7 ± 13.3	95.1 ± 8.1	n.s
Constant score (point)	Preop	57.0 ± 13.7	57.8 ± 9.5	n.s
	POD 6M	66.8 ± 13.8	67.5 ± 6.3	n.s
	POD 1Y	70.2 ± 9.5	71.9 ± 3.9	n.s

CHL coracohumeral ligament, *pVAS* visual analog scale for pain, *ASES* American shoulder and elbow surgeons, *Preop* preoperative, *POD* postoperative day, *M* months, *Y* year

at 1-year follow-up. Functional scores (Constant score and ASES score) also showed significant improvement after surgery (57.3 ± 11.1 to 70.9 ± 7.5 and 57.5 ± 15.9 to 93.9 ± 10.6, respectively; all $P < 0.05$). However, there was no significant difference in functional scores and pVAS between the two groups (Table 2).

Regarding anatomical healing, we assessed tendon integrity using either MRI ($n = 147$) or ultrasonography ($n = 5$) at 1 year after surgery. Ultrasonography was used in a minority of cases (3 cases in Group I, 2 cases in Group II) in each group due to cost issues. There was no significant difference in the healing failure rate between the two groups (6 cases in Group I (7.9%), 2 cases in Group II (2.6%); n.s.) (Table 2). There was also no significant relevance between postoperative ER stiffness (< 30°) and healing rate (n.s.). No patient experienced any postoperative complications related to CHL release, such as instability symptom or infection.

Forward flexion, ER at side, and IR at back showed no difference during the preoperative period. All patients showed a trend towards decreased ROM at postoperative 3 months, but recovered at postoperative 6 months to ranges similar to the preoperative values. In terms of forward flexion and IR at back, there was no significant difference between the two groups at postoperative 3 months, 6 months, and 1 year (all n.s.). ER at side at postoperative 3 months in Group II was better than that of Group I (48.6° ± 11.6° vs. 38.4° ± 13.0°, $P < 0.001$), but there was no significant difference between the two groups at postoperative 6 months and 1 year (all n.s.) (Table 3).

Subanalysis was conducted to evaluate whether the difference of ER at side between the two groups correlated with tear size. All patients were divided into two subgroups in each group: small-to-medium sized tear (< 3 cm) and large-to-massive sized tear (≥ 3 cm or involving subscapularis tear). Considering only patients with a small-to-medium sized tear at postoperative 3 months, ER at side was 49.8° ± 10.9° in Group II versus 37.8° ± 13.1° in Group I ($P < 0.001$). In patients with a large-to-massive sized tear, however, there was no significant difference in ER

Table 3: Comparison of range of motion at postoperative 3, 6 months, and 1 year between the two groups.

ROM	Period	Group I (no-releasing)	Group II (CHL-releasing)	*P value*
FF (°)	POD 3M	141.6 ± 17.6	142.0 ± 19.1	n.s
	POD 6M	164.4 ± 17.2	161.5 ± 10.3	n.s
	POD 1Y	162.8 ± 27.7	165.0 ± 7.2	n.s
ER at side (°)	POD 3M	38.4 ± 13.0	48.6 ± 11.6	< 0.001
	POD 6M	72.1 ± 15.9	67.2 ± 16.0	n.s
	POD 1Y	70.3 ± 20.8	69.3 ± 12.1	n.s
IR at back (level)	POD 3M	12.2 ± 2.9	12.0 ± 2.8	n.s
	POD 6M	8.6 ± 2.6	9.1 ± 2.2	n.s
	POD 1Y	8.4 ± 1.8	8.0 ± 1.3	n.s

ROM range of motion, *CHL* coracohumeral ligament, *FF* forward flexion, *ER* external rotation, *IR* internal rotation (*1–12* thoracic vertebrae 1–12, *13–17* lumbar vertebrae 1–5, *18* sacrum), *POD* postoperative day, *M* months, *Y* year

at side at postoperative 3 months between the two groups (n.s.) (Fig. 3). We also calculated the change of ER angle (ER angle at postoperative 3 months—preoperative ER angle) in each subgroup; there was a significant difference in the change of ER angle (−34.1° ± 16.6° in Group I vs. −19.0° ± 17.4° in Group II) in the small-to-medium sized tear ($P < 0.001$). However, there was no significant difference in the change of ER angle (−22.1° ± 22.6° in Group I vs. −29.0° ± 20.1° in Group II) in the large-to-massive sized tear (n.s.).

Discussion

The principal finding of this study was that the significantly better ER in the early postoperative period was achieved without acute complications through the CHL release, which was effective in patients with a small-to-medium sized rotator cuff tear. Therefore, CHL release in arthroscopic rotator cuff repair can be used as a selective procedure to prevent postoperative stiffness in patients that may benefit from this procedure with decreased preoperative ER compared to the normal side.

The incidence of postoperative stiffness after rotator cuff repair has been reported to vary according to the definition of stiffness. Brislin *et al.* stated that 8.6% of patients developed postoperative stiffness at a mean of 3 months after surgery [4], while Parsons *et al.* showed that 23% of patients had a stiff shoulder at 3 months after surgery [31]. Chung *et al.* demonstrated that the incidence of postoperative stiffness was 18.6% at 3 months after rotator cuff repair, 2.8% at 6 months, and 6.6% at final follow-up [7]. Shoulder stiffness that occurs after surgery can have a detrimental effect on surgical outcome and patients' quality of life [4, 11, 14]. Additional procedures, such as manipulation under anesthesia or arthroscopic capsular release, could be considered if stiffness does not resolve [6, 13, 18, 28]. Despite these important clinical factors, few studies have investigated surgical procedures to prevent postoperative stiffness. Oh *et al.* reported that subacromial injection of an anti-adhesive agent after arthroscopic cuff repair had a tendency to induce faster recovery of forward flexion at 2 weeks postoperative [27]. The authors also attempted various surgical procedures to prevent postoperative stiffness, such as preventive capsular release or early passive exercise during the immediate postoperative period [6, 13, 17, 18, 28]. As these

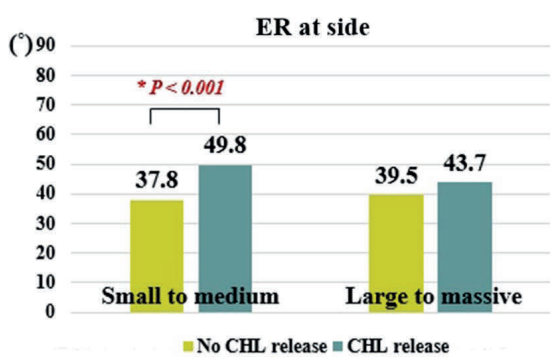


Fig. 3: Considering only patients with a small-to-medium sized tear at postoperative 3 months, ER at side in Group II was 49.8° ± 10.9° versus 37.8° ± 13.1° in Group I ($P < 0.001$). In patients with a large-to-massive sized tear, however, there was no significant difference in ER at side at postoperative 3 months between the two groups (n.s.). *CHL* coracohumeral ligament, *ER* external rotation.

attempts have proven to be meaningful procedures, CHL release which can resolve the major histologic factor of stiffness was also considered as a meaningful procedure to prevent postoperative stiffness in this study.

The CHL originates from the base of the coracoid process, and covers the subscapularis, supraspinatus, and infraspinatus tendons. It broadens to merge with the rotator interval capsule and inserts on both the lesser and greater tuberosities. Numerous previous studies have indicated that the CHL is the primary restraint to ER. Neer *et al*. reported that CHL in fresh specimens was tight with maximal ER at side [25], and Mengiardi *et al*. demonstrated that CHL thickness on MR arthrography correlated with ER in frozen shoulder [23]. The most common elements involved in the development of fibrosis in a stiff shoulder include the CHL and the interval tissue between the base of the coracoid process and the subscapularis [15, 16, 25, 26]. Histological analysis of fibroblastic proliferation of the CHL within the rotator interval demonstrates the loss of excursion between the subscapularis and supraspinatus tendons [1]. Park *et al*. demonstrated that obliteration of the subcoracoid fat triangle was significantly more common in the early stages of adhesive capsulitis [30]. Although the etiology of acquired ROM loss after shoulder surgery remains unclear, postoperative stiffness may result from not only adhesions in the subacromial and subdeltoid space but also in the subcoracoid space at the interface of shoulder motion. The cadaveric study of Neer *et al*. reported that ER could be increased up to average of 32° on sectioning CHL only [25]. According to the current findings of increased ER to average of 48° in CHL releasing group at the early postoperative phase, it could be determined that CHL release can maximize the effect of rehabilitation, especially ER at side, as well as being agreement with these previous reports [1, 15, 16, 23, 25, 26, 30].

There was no significant difference in ROM and clinical outcomes between the two groups at postoperative 6 months and 1 year. Namdari *et al*. suggested that early postoperative limitation of motion after rotator cuff repair is associated with restricted preoperative motion; however, most patients recover well [24]. Parsons *et al*. showed that early limitation of motion does not result in long-term stiffness after surgery [31]. Several postoperative clinical factors, such as rehabilitation and injection usage, could affect stiffness during the late postoperative period. For patients with painful stiffness in the early period, the authors encouraged vigorous stretching exercises after subacromial steroid injection, which did not influence the rate of healing. Thus, these factors could mask the effect of CHL release on improvement of ROM in the late postoperative period, similar to previous reports [24, 31].

CHL could be released from the undersurface of the coracoid process at the outside of the glenohumeral joint without creating a rotator interval defect. If CHL release was performed inside the glenohumeral joint, it would have damaged the rotator interval, including the superior glenohumeral ligament, resulting in a rotator interval defect. When present, these defects may predispose the patient to pain and instability symptom related to increased humeral head translation and may cause additional injury to this interval tissue [9, 32]. Hence, the authors tried to preserve the substantial tissue of the rotator interval during the release of the CHL from the coracoid process. Furthermore, CHL release from the coracoid process did not lead to instability symptom

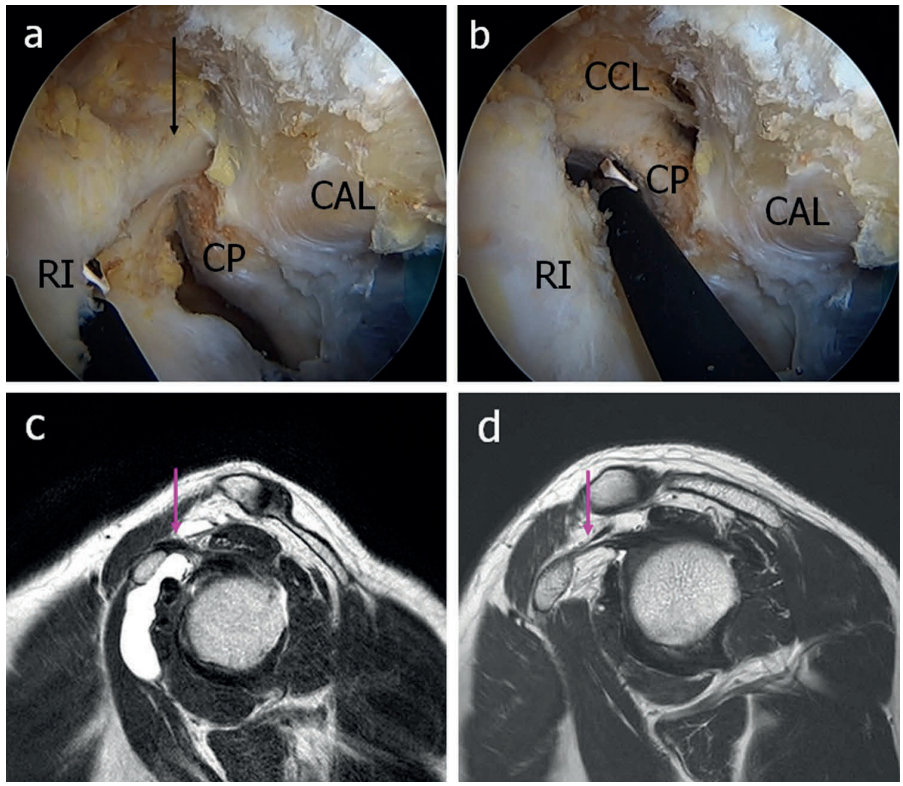


Fig. 4: A 48-year-old patient with a large-sized rotator cuff tear treated by arthroscopic rotator cuff repair with a single row. Arthroscopic subacromial decompression and acromioplasty was performed; then, the coracohumeral ligament (black arrow) was released from the undersurface of the coracoid process without creating a rotator interval defect using a radiofrequency device through the lateral portal (**a, b**). The coracohumeral ligament (purple arrow) regenerated after surgery, which could be confirmed on magnetic resonance imaging at 1 year after surgery, without instability or any related symptoms (**c, d**). *RI* rotator interval, *CP* coracoid process, *CAL* coracoacromial ligament, *CCL* coracoclavicular ligament.

during range of motion. The CHL could be reconstructed with new organized fibrous tissues after surgical resection, which arise from the base of the coracoid process. Levy *et al*. reported regeneration of the coracoacromial ligament from the periosteum of the new edge of the acromion during second-look arthroscopy, which revealed well-organized bundles of collagen fibers macroscopically and on histologic analysis [21]. In the current study, the CHL also regenerated, which could be confirmed on MRI at 1 year after surgery (Fig. 4), and no patient complained of instability or any related symptoms.

Surgeons perform interval slide in continuity to mobilize the retracted anterosuperior rotator cuff in patients with a massive tear. Lo *et al*. asserted that a partial CHL release improved the mobility of both the subscapularis and posterosuperior rotator cuff, which resulted in more lateral

excursion of a medial repaired rotator cuff [22]. Additionally, a biomechanical study showed that CHL release reduced the strain of the repaired rotator cuff [12]. In the current study, postoperative stiffness in patients with a large-to-massive sized tear was not evident. This could be explained by the fact that adequate release of soft tissue involving the CHL and rotator interval to mobilize the retracted tendon in cases of large-to-massive sized tear would lead to good ROM in the early postoperative period, including ER range. Therefore, further large-numbered and long-term follow-up study would be needed according to the size of rotator cuff tear.

The authors believe that the current study is the first attempt to demonstrate the effect of CHL release from the coracoid process without making a rotator interval defect to prevent postoperative stiffness after arthroscopic repair of small-to-medium sized cuff tear. Some limitations of the current investigation include the potential for typical biases of a retrospective study. Since there were no similar studies related to the CHL release for prevention of postoperative stiffness, a power study for sample size calculation was not possible. Second, as the authors divided patients into two groups depending on whether CHL had been released or not at the time of surgery, there would be time-dependent bias. However, all procedures were performed by one senior surgeon, who was sufficiently experienced and standardized all steps during arthroscopic surgery. Third, even though ultrasonography was used instead of MRI for the assessment of tendon integrity in some cases with cost issues, there would be little bias by the difference in methods with respect to small numbers. Finally, the difference of 12° in ER between two groups at 3 months after surgery may have little clinical significance even with the statistical meaning. However, CHL release could be performed within a short time without related complications in this study. Therefore, if preoperative ER was decreased compared to the normal side, CHL release can be used to prevent stiffness or to restore ER, postoperatively. It may be a useful procedure to produce faster recovery in early postoperative ROM after rotator cuff repair through the encouragement of rehabilitation.

Conclusions

In arthroscopic rotator cuff repair, CHL release from the coracoid process without creating a rotator interval defect could be an effective and safe method to prevent early postoperative stiffness, especially ER at side in patients with a small-to-medium sized tear. Therefore, CHL release can be used as a selective procedure to prevent postoperative stiffness in patients that may benefit from this procedure with decreased preoperative ER compared to the normal side.

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Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical approval: The Institutional Review Board approved an exemption for this study due to its retrospective design (IRB No.: B-1808/484-106, Seoul National University Bundang Hospital Institutional Review Board).

Informed consent For this type of study, formal informed consent was not required.

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Primary Screw Perforation or Subsequent Screw Cut-out Following Proximal Humerus Fracture Fixation Using Locking Plates: A Review of Causative Factors and Proposed Solutions

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Abstract

The surgical treatment of proximal humerus fractures remains controversial primarily due to the high complication rate associated with the available fixation methods. In an attempt to reduce the incidence of serious complications and subsequent poor clinical outcomes, proximal humerus locking plates have become popular but even these implants cannot overcome the risk of complications, especially those associated with loss of fracture reduction and screw cut-out/migration through the humeral head. In an attempt to address these issues, we have reviewed the literature, investigating the most likely causes for these predominantly mechanical complications and propose technical solutions.

Keywords Proximal humerus fracture, Locking plate fixation, Fixation failure, Screw perforation, Osteoporosis

Introduction

Fractures of the proximal humerus are common and predominantly occur in older patients [1]. After fractures of the distal radius and proximal femur, proximal humerus fractures are the next

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most common fracture in the elderly [2]. Furthermore, with an expanding elderly population, the incidence of these fractures is steadily increasing [3]. The morbidity associated with these fractures and their impact upon a patient's functional ability is frequently significant especially if non-anatomical fracture positions are accepted, and there is a subsequent delay to rehabilitate the shoulder.

The management of proximal humerus fractures remains challenging and similar to many fractures, a variety of operative treatment options exist as well as the option of non-operative management. In terms of surgical management, currently the three most common surgical interventions are open reduction and internal fixation (ORIF), hemiarthroplasty and more recently, reverse shoulder arthroplasty. For most surgeons, treatment choice is largely dependent upon the fracture type, taking into consideration the degree of fracture comminution and displacement, patient age and functional demands, as well as the surgeon's personal experience with treating these injuries. ORIF using locking plates offers the potential benefit of restoring anatomical alignment, that retains the patient's own gleno-humeral joint and provides optimal tensioning of the patient's joint capsule, rotator cuff and deltoid, ideally permitting early active mobilisation. Studies have also shown that ORIF, performed by experienced surgeons, leads to good post-operative clinical outcome scores and post-operative range of motion, however, ORIF is associated with a significant complication rate (15%) and re-operation rate (12.7%) compared with conservative treatment [4]. These iatrogenic complications include inability to achieve optimal fracture alignment, loss of fracture reduction, hardware failure/mal-positioning, malunion/non-union, avascular necrosis (AVN), infection, nerve injury and dislocation. However, the commonest iatrogenic causes leading to re-operation are loss of fracture reduction and screw cut-out/migration, that predominantly result from technical errors on behalf of the operating surgeon [5]. A systematic review of the literature in 2011 by Sproul *et al*. looked at 12 studies with a total of 514 patients and found that screw perforation occurred in 8% of patients and was the most common cause for re-operation [6]. More recently in 2013, in a cohort of 121 patients, Jost *et al*. found secondary screw cut out in 57% of patients [7].

It is evident therefore, that this particular fixation technique has its benefits but the frequency of screw cut out and screw perforation is unacceptably high. This review will focus upon the potential patient factors and technical factors that lead to these complications in an attempt to address and reduce their occurrence.

Patient Factors

Bone Quality

Fractures of the proximal humerus most commonly occur in patients over 60 years old (70%) and tend to be associated with low bone mineral density (BMD) making fixation more challenging [8]. The quality and quantity of humeral head bone are critical, with local osteoporosis affecting implant anchorage [9]. Subsequently, a common mode of failure following ORIF in

osteoporotic bone is 'bone failure' rather than implant breakage. Krappringer *et al*. demonstrated that 'local' BMD and patient age significantly influenced the failure rate, despite the initial extent of fracture displacement or angulation [10]. They were unable to demonstrate any correlation between failure of fixation and surgical technique [10]. Pre-operatively, dual-energy x-ray absorptiometry or peripheral quantitative computed tomography can be used to assess BMD and assist in surgical decision making. However, these investigations are rarely available within the emergency setting and in the majority of cases are considered by most surgeons to be unhelpful given the apparent need to treat grossly displaced fractures and the delay in treatment associated with undertaking these investigations. Although not widely used, Tingart *et al*. have proposed a readily available alternative, using the combined cortical thickness of the proximal humeral diaphysis as a predictor of BMD pre-operatively, and they concluded that a cortical thickness of less than 4 mm is highly indicative of a low BMD [11]. Similarly, Newton *et al*. used cortical thickness to calculate a medial cortical ratio (MCR = diameter of diaphysis/medial cortical thickness) and found that loss of fixation was three times more likely in those patients with a MCR <0.16 [12]. We feel that consideration of patient BMD is overlooked or undervalued when considering treatment options and increased awareness is essential when planning to proceed with ORIF as low BMD will affect the stability of the fixation at the bone-screw interface. Whilst we cannot improve a patient's local BMD acutely, techniques such as cement augmentation have been proposed to improve the bone-screw interface [13].

Fracture Configuration

The fracture configuration must also be taken into consideration when deciding whether or not to proceed with ORIF. A number of different classification systems exist for the evaluation of fractures of the proximal humerus, one of which is the Neer classification that is based upon the number of fracture parts [14]. In terms of prognosis, the three and four part fractures are more likely to suffer complications and have worse outcomes than the less complex fracture patterns [15]. Fracture comminution, especially of the medial calcar, and the tuberosities, and bone loss also need to be considered. Whilst much of this information can be derived from radiographs, a CT scan with 3D image processing is significantly more accurate and we would therefore recommend that this investigation is undertaken routinely in the pre-operative work-up for all but the simplest fracture types. As has been reported by several authors, a short calcar metaphyseal segment (length less than 8 mm) and medial hinge displacement (>2 mm) is associated with a significant increase in the risk of developing AVN due to the associated damage to the inferior joint capsule and subsequent blood supply to the humeral head [16, 17]. The risk of AVN is even greater when this fracture type is associated with displaced fractures involving both the greater and lesser tuberosities. However, in addition to the risk of AVN, the reduced mechanical stability that results from metaphyseal comminution, also described as loss of the medial column, has statistically significant correlation with loss of reduction [18]. This loss of reduction and head collapse increases the chance of subsequent screw perforation and/or cut out since the fracture is unable to load bear adequately and depends almost entirely upon the locking plate and screws to maintain the

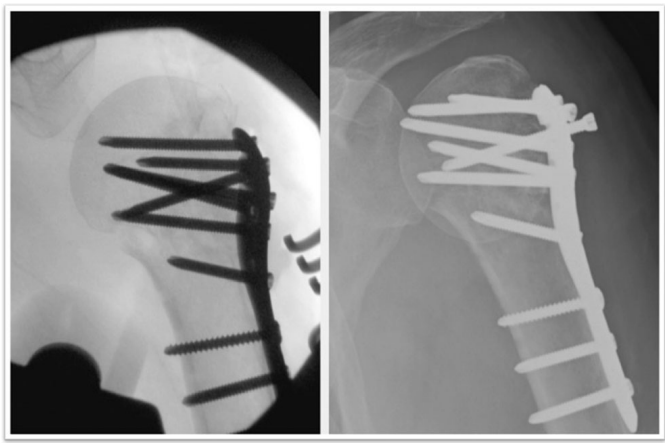

Fig. 1: Intra & post-operative radiographs showing a proximal humerus fracture with metaphyseal comminution, in which the medial column instability was insufficiently addressed. This lead to subsequent head collapse, screw perforation of the head and some screws backing out within 6 weeks of primary fixation. This case required surgical revision.

reduction. An example of this is seen in Fig. 1. In one series, an incompetent medial column led to 30% screw perforations compared with 6% for fractures with an intact medial column capable of load transfer [19].

Surgeon/technical Factors

Fracture Reduction

The primary objective of surgical fixation is to achieve effective stabilisation in an adequately reduced fracture. Within fractures of the proximal humerus, accurate anatomical fracture reduction has been shown to significantly reduce complication rates and improve clinical outcomes [20]. While we strive for anatomical reduction, this reduction must also have a degree of inherent stability with bone to bone loading. As the proximal humerus is an eccentrically loaded joint, if this independent stability is not achieved, the reduction and alignment relies almost entirely upon the internal fixation device used. This increases the loading of the subchondral screws within the humeral head, significantly increasing the likelihood of loss of fracture reduction and the subsequent risk of secondary screw perforation, particularly in osteoporotic bone.

The three most important aspects of proximal humerus fracture reduction are; obtaining medial column support, restoration of the neck-shaft angle and reduction of the tuberosity fragments. As previously discussed, achieving medial column stability is arguably the most important and most challenging aspects in treating these fractures to ensure good load transfer between the humeral head and the shaft. Clinically this is critical in preventing loss of reduction following fixation [21]. In the simpler fracture patterns calcar and medial metaphyseal comminution is less common. However, in the more complex fractures it is a significant issue and adequate restoration of the fracture alignment may still not provide sufficient bone to bone load bearing through the medial column and in these circumstances, it is important to recognise the mechanical failings of the construct and to supplement the fixation.

In patients with a varus mal-reduction of greater than 5 degrees, there is an increased risk of progressive varus subsidence of the humeral head [22]. Additionally, Agudelo *et al.*, showed that a varus mal-reduction resulting in a neck-shaft angle of less that 120 degrees was significantly associated with an early loss of fixation [23]. Hertel also advised of the importance of near anatomical reduction of the tuberosities in providing a stable platform that suitably supports the humeral head and again reduces the risk of screw penetration by placing cortical bone between the locking plate and the cancellous bone of the humeral head [24]. This is highlighted in Fig. 2.

Implant Selection

The application of locking screws and fixed angle convergent and divergent screws is thought to increase stability and pull-out strength, which is particularly relevant in osteoporotic bone [25, 26]. The backing out of screws is also less of an issue with these plates, providing that drill direction and the screw insertion angle is correct allowing accurate alignment of the threads on the heads of the screws with the threads in the plate.

There is, however, variation in locking plate design including overall profile, manufacturing material and screw configurations. Although these variations are small they are likely to have some impact upon fixation failure. Specifically, implant stiffness has a direct effect upon the bone-implant interface. Under cyclic loading, rigid implants lead to early loosening and failure of the bone-implant interface presumably due to the mechanical mismatch of the bone and the implant [27]. Less rigid and smaller-dimensioned implants, although potentially 'poorer' in terms of the early stability that they offer, exhibit lower peak stresses at the bone-implant interface compared with more rigid and over-sized osteosynthetic devices, and may be better suited to the treatment

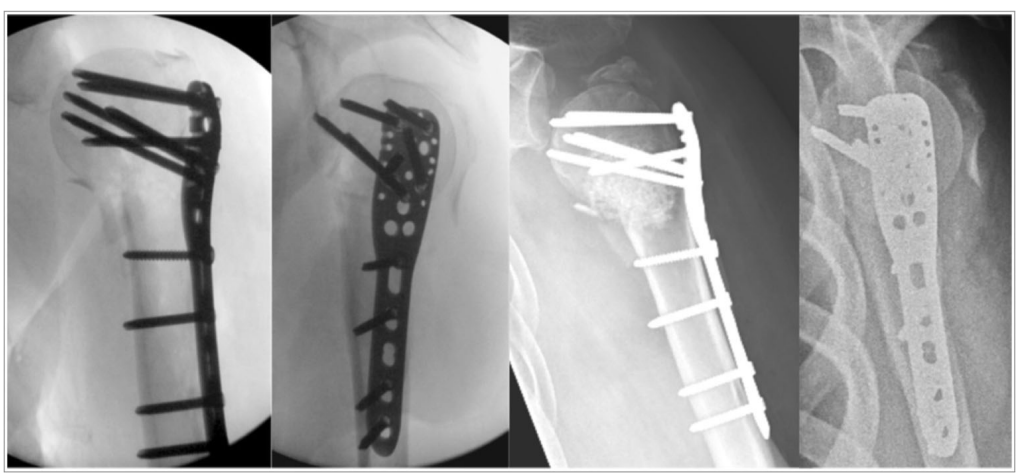

Fig. 2: Intra & post-operative radiographs showing a proximal humerus fracture in which there was post-operative loss of reduction and screw perforation. This can be attributed to the metaphyseal comminution and a failure to reduce the tuberosity fragments. Additionally, the initial screw choices are too long.

of osteoporotic fractures where screw cut out is a significant problem. With this in mind, there is ongoing work to produce proximal humeral locking plates that have an elastic modulus that is more similar to that of human bone whilst still maintaining implant strength. Lab based research investigating carbon fibre reinforced polyetheretherketone (PEEK) is extremely promising and clinical data is comparable but not yet conclusive [28,27,30].

Surgical Technique

Restoring the Medial Column

Where medial column stability is suboptimal, fracture stability can be improved using; a medial supporting screw(s) that is inserted into the inferior most portion of the humeral head; by using an endosteal implant; through impaction of the shaft into the humeral head fragment to restore load transfer through the 'new' calcar or by inserting an intramedullary fibular strut graft. The literature demonstrates that a medial support screw(s) enhances the primary stability of locking plate fixation in the majority of fixations and therefore should be used in all cases where technically feasible to support the medial column [13, 31, 32]. An endosteally placed fibular strut graft inserted in addition to a lateral locking plate has been shown to increase the maximum failure load and construct stability significantly [33]. This technique works in two ways. Firstly, it recreates some of the absent medial column loading characteristics, and secondly, it provides additional support for the locking screws that improves the overall rigidity of the construct [34,33,36]. A systematic review by Saltzman *et al*. has shown the use of fibular strut grafts as an adjunct to ORIF of the proximal humerus to have acceptable functional outcomes and to diminish the rate of screw perforation to 3.7% [37]. In our unit, when treating patients with markedly comminuted 4-part fractures or grossly unstable varus fractures, the senior author prefers to insert an intramedullary non-locking plate that is attached to the inner aspect of the head/calcar region, with the stem of the plate inserted into the inner aspect of the shaft of the humerus to create a 'peg' that prevents varus displacement of the fracture and promotes medial column load bearing. An example of this is shown in Fig. 3. Early results from our small series of six patients are promising with no significant loss of reduction, screw cut out and or subsequent development of AVN. Again with small numbers, Hettrich *et al*. have used a similar technique in four patients and demonstrate no significant loss of reduction in this cohort with clinical outcomes that equal patients who have been treated with endosteal fibular allografts [38]. However, the use of intra-medullary adjuncts is not routine for most surgeons as they often require a more extensive soft tissue dissection and greater disruption of the fracture fragments to access the intra-medullary canal, that presumably increases the risk of further vascular impairment of the humeral head. For these reasons, these techniques tend to be reserved for those cases where medial column support or calcar comminution is of particular concern and where arthroplasty is not a realistic option.

In some circumstances, and especially in elderly patients where there is marked comminution of the surgical neck but who otherwise have well vascularised humeral head fragments, it is usually

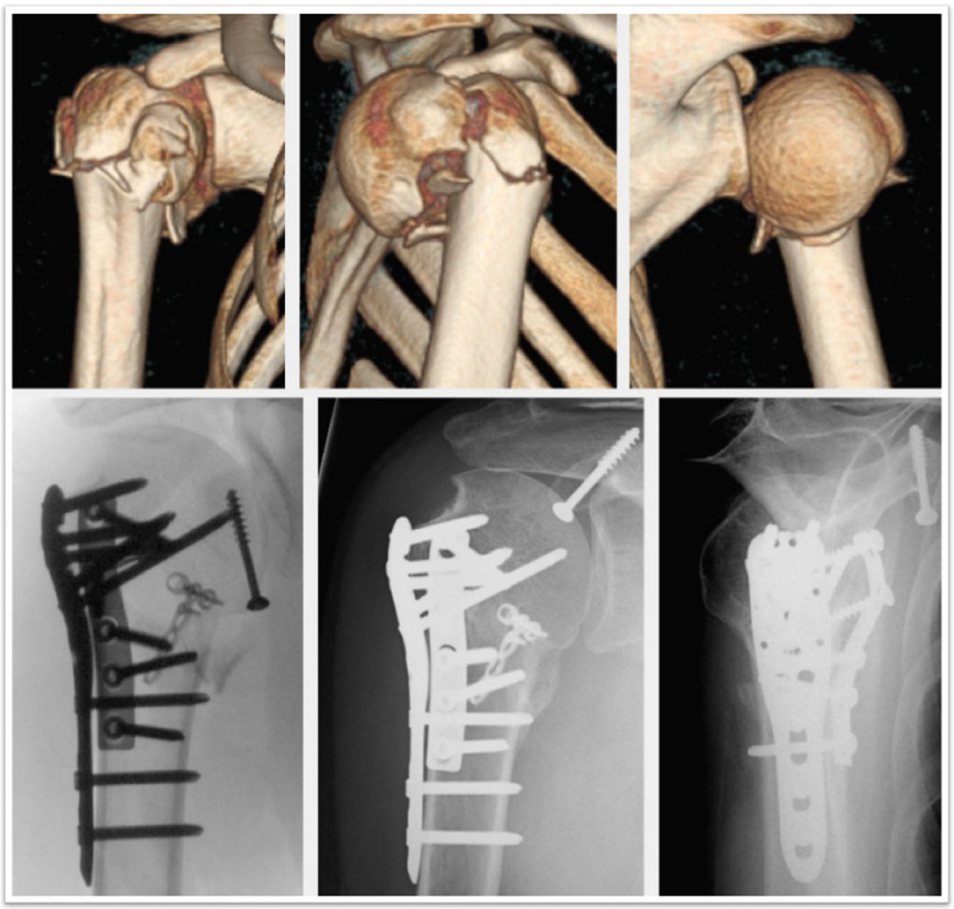

Fig. 3: CT reconstruction and radiographs showing a significantly comminuted fracture-dislocation of the proximal humerus treated with open reduction and internal fixation. Due to the significant comminution and subsequent instability, a supplementary anterior plate and intra-medullary plate were used to achieve adequate stability.

possible to restore medial stability without reconstructing the calcar. In these situations, a load bearing medial column is 'reconstructed' by impacting the shaft of the humerus into the head (see Fig. 4) while maintaining the correct neck-shaft angle. Admittedly, this can shorten the humerus by up to 2 cm, but without obvious functional detriment to the patient in this age group. Also, since the rotator cuff remains attached to the correct anatomical insertions and is therefore adequately tensioned, cuff function is often good after surgery. Essentially it is mainly deltoid function that can be affected by humeral shortening, but in this elderly patient group, this is often well tolerated. In addition, since the impacted configuration is stable, the risks of subsequent head collapse and screw perforation/migration are significantly reduced even in the presence of significant osteoporosis.

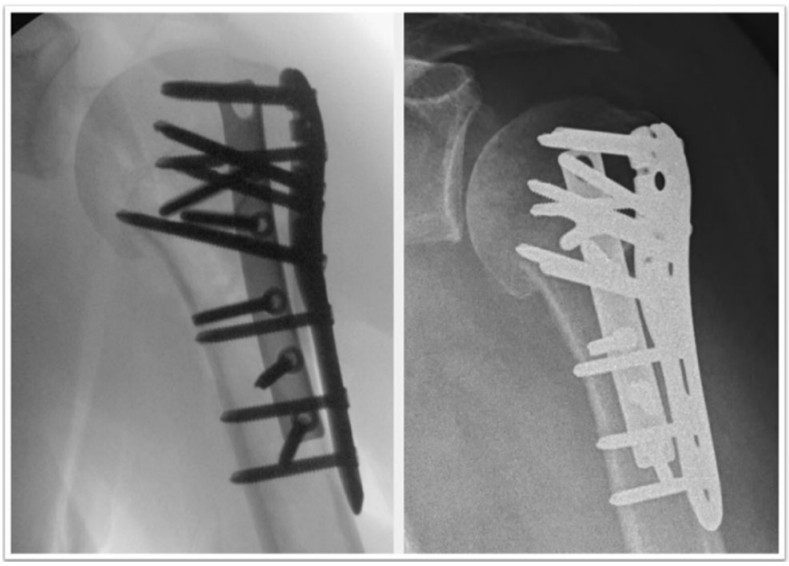

Fig. 4: Radiographs showing a proximal humerus fracture in which the surgeons chose to impact the head on the shaft due to significant instability of the head when reduced to the anatomical positioning. Whilst this has resulted in slight shortening of the humerus, the reduction achieved was stable and subsequently maintained in the post operative period.

Screw Placement

Most proximal locking plates available in today's market have multiple locking screw options allowing for variation in screw placement and organisation in diverging and converging screw arrangements. Liew *et al*. propose that screw placement has a direct impact on pullout strength, with screws placed centrally within the humeral head having the optimal screw fixation strength, whereas the poorest fixation is achieved with screws inserted into the antero-superior region of the humeral head [39]. They attributed these findings to the previously examined trabecular patterns in the humeral head, with increased trabecular bone density present in the central, inferior and posterior regions, and subsequent improved fixation strength [40]. Similar results have been shown by Tingart *et al*. who demonstrated the antero-superior region of the humeral head to have the lowest BMD and subsequently lowest screw pull out strength [41]. They found no difference between the infero-posterior, supero-posterior and central regions. Additionally, the accurate placement of the calcar screws within the bottom 25% of the humeral head has also been shown to decrease the risk of fixation failure [42].

Screw Length

Whilst taking into consideration that some regions of the humeral head contain denser bone that others, there is no doubt that the strongest bone within the humeral head is immediately

subchondral, adjacent to the subchondral plate [43]. However, in some individuals, even this bone is of poor quality and due to the weak bone giving poor feedback while drilling leading to surgeons drilling too far into or through the subchondral bone resulting in screws that are too long or prone to penetrate the subchondral bone should any subsidence occur. Screw perforation of the humeral head is commonly seen in this patient group. Screw penetration can be primary, due to the screws being placed too close to the articular surface or indeed perforating the articular surface intra-operatively, leading to patient morbidity from screw impingement upon the glenoid, chondrolysis and the need for further surgery especially if the prominent screws involve the major articular component of the humeral head. One technique that can be utilised to reduce the risk of this complication is placing the drill in reverse after drilling through the lateral humeral cortex. This negates the cutting edges of the drill bit and instead converts the drill bit into a revolving blunt probe that is less likely to penetrate the cortical bone despite still being sufficient to penetrate the cancellous bone. However, in extremely osteoporotic bone, even this technique does not completely eradicate the risk of drill perforation and the need to assess the progress of the drill, in multiple planes using fluoroscopy is required. Standard intra-operative images may miss nearly half of screw penetrations, and it is recommended that a combination of four projections (axial view with 30 degrees abduction and antero-posterior views in internal rotation, neutral and external rotation) have 100% sensitivity for identifying screw perforation [44].

Secondary penetration occurs due to loss of fracture reduction and head fragment subsidence. Brunner *et al*. reported 35 screw penetrations (22 primary and 13 secondary) in a cohort of 158 patients [45]. In both types of penetration, surgical technique is invariably the main culprit. With proximal humerus locking plates, the locking of the threaded screw heads within the plate provides increased axial and angular stability. However, if there is head collapse post fixation, the screws are unable to back out and therefore the screws penetrate through the head. A cadaveric study undertaken by Erhardt *et al*. showed that the risk of perforation could be significantly reduced by increasing the number of screws inserted into the head and by using an infero-medial support screw, also suggested by Hertel [24, 46]. They subsequently recommend using a minimum of five screws inserted into the humeral head and the insertion of an infero-medial support screw; the latter being of even greater importance should it prove impossible to restore the medial column accurately. The use of blunt tipped locking bolts rather than sharp tipped screws within the humeral head may also have a positive impact on reducing perforation rates.

Augmenting the Fixation

To further improve the stability of the fixation a number of other surgical techniques have been described in the literature. In three and four part fractures, once reduced, fixation of the tuberosities can be difficult to achieve with a locking plate alone and so additional fixation with sutures or supplementary plates may be required [47]. Cement can be utilised to augment screw fixation to reduce motion at the bone-implant interface [48]. In addressing metaphyseal comminution, the addition of calcium phosphate cement has been shown to decrease fracture settling and

significantly decrease intra-articular screw penetration. Additionally, the use of bone graft or femoral head allograft has been described [49].

Conclusion

As with the surgical treatment of all fractures, it is important to get the fixation right the first time, thereby decreasing the incidence of re-operation and patient morbidity. Fractures of the proximal humerus exemplify this more than most, where fixation remains a technical challenge despite the improved understanding of fracture patterns and their inherent associated instabilities, head vascularity and ever improving implant designs. However, the loss of reduction with subsequent screw cut-out/migration resulting in head perforation is influenced by both patients' bone quality, fracture configuration and the surgical techniques used. Therefore, patient selection is undoubtedly key, with consideration given to patient age, fracture configuration, including medial column involvement, and degree of osteoporosis, prior to proceeding with fixation. Anatomical reduction is the aim, but achieving inherent bone to bone mechanical stability is questionably more important especially if an anatomically acceptable and inherently stable fracture configuration can be obtained. Varus mal-reduction and lack of medial column support are high predictors of failure and should be avoided at all cost. Finally, in addition to obtaining optimal fracture reduction and/or fracture stability, there is good evidence that a medial column support screw should be used routinely. Also, a minimum of five screws should be inserted into the humeral head aiming if possible for the central, infero-posterior and supero-posterior regions. The effects of implant stiffness in osteoporotic bone needs further clinical assessment and research to try and achieve a better biomechanical bone-implant match. Whilst current low-profile titanium or stainless steel locking plates are currently favoured, we believe research into the use of other composite materials may produce more biomechanically compatible implants that could yet further reduce the incidence of screw perforation while also enhancing fracture healing. Given the potential complexity of proximal humerus fractures, especially in the presence of significant osteoporosis, surgeons willing to perform ORIF of proximal humerus fractures also need to have the surgical ability and experience to proceed to an arthroplasty where the bone quality or fracture configuration is found to be unsuitable for fixation intra-operatively or the head of the humerus is devoid of a blood supply.

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Compliance with ethical standards

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Awake Endoscopic Transforaminal Lumbar Interbody Fusion: A Technical Note

Alexander J. Butler, G. Damian Brusko, Michael Y. Wang

Abstract

Background: Advances in modern spinal fusion techniques have allowed for less peri-operative morbidity and more rapid recovery from surgery. The addition of endoscopy to minimally invasive surgery (MIS) fusion techniques represents the latest progression of efforts to minimize the impact of surgical intervention.

Technique: MIS transforaminal lumbar interbody fusion (TLIF) is performed endoscopically through a sub-centimeter working portal. Patients undergo light conscious sedation and remain awake to facilitate feedback with the surgeon and enhance post-operative recovery.

Results: Previously reported results of the first 100 cases performed by the senior author at a single institution are summarized. This cohort has been characterized by brief post-operative length of stay, low complication profile, and marked improvement in patient-reported outcomes scores, with no cases of pseudarthrosis at 1-year follow up.

Conclusions: The latest technical considerations and adaptations of a novel technique for endoscopic MIS spinal fusion without general anesthesia are described. A refined surgical technique and anesthetic protocol are presented in detail with recommendations for the successful implementation and performance of the procedure.

Keywords Fusion, Spinal surgery, Endoscopy, MIS, TLIF, Technique

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Introduction

Over many decades, innovations in spinal surgery techniques have evolved to better meet patients' needs and modern healthcare systems' demands. Rates of spinal surgery have increased steadily, as well, particularly in the growing elderly population [2, 9]. Lumbar fusion is regarded as one of the most painful and debilitating of surgical procedures [4], and patients increasingly opt to avoid the traditional open surgical approach in favor of minimally invasive surgery (MIS), desiring reduced pain and fewer complications.

Various MIS techniques have been developed, all of which aim to improve clinical outcomes, reduce morbidity, and limit post-operative pain. For lumbar fusion in particular, the MIS transforaminal lumbar interbody fusion (TLIF) has become a favorable option for the treatment of degenerative lumbar disease [8]. First described in 2003, the MIS TLIF employs a tubular retractor docked over the facet joint to facilitate total facetectomy and both ipsilateral and contralateral discectomy prior to placement of an interbody cage, followed by percutaneous pedicle screws with rod fixation [3].

As with the advent of MIS fusion techniques in the previous decade, the recent development of endoscopic TLIF techniques has further advanced this approach to lumbar fusion surgery. Although endoscopes were first used in spinal surgery in the 1980s, when Parviz Kambin employed them for percutaneous discectomies, endoscopic innovations in lumbar fusion have occurred more recently [1, 10]. Richard Fessler and colleagues established endoscopy as a safe and useful adjunct to MIS TLIF, resulting in equivalent outcomes and less peri-operative morbidity in a small series [6]. Description of Kambin's triangle and subsequent cadaveric analyses have identified operative zones in which an endoscopic TLIF may be safely performed [5]. More recent data have validated the incorporation of endoscopic approaches for lumbar fusion to augment reductions in post-operative pain levels, opioid use, and length of hospital stay [12]. Therefore, the endoscopic TLIF may be a more appealing surgical option for patients resistant to undergoing even the traditional MIS TLIF, which still necessitates an open incision for muscular dissection to facilitate tube placement.

We have previously described initial results of our novel endoscopic MIS technique without the use of general anesthesia for one- and two-level TLIFs [11]. Here, we focus on details and improvements of surgical and anesthetic techniques and summarize the results from the first 100 treated patients to ascertain where further refinements in the technique can be achieved.

Technique

Anesthetic Technique

Conscious sedation is administered by our dedicated anesthesia team by way of a continuous infusion of propofol and ketamine. Initially, medications are titrated to achieve a light to moderate sedation level; spontaneous ventilation and purposeful response to verbal or noxious stimuli

are maintained. No opioid medication or additional spinal, epidural, or general analgesic is used. Supplemental oxygen is provided via nasal cannula or face mask. As the patient is positioned prone without an advanced airway, the experience and comfort level of the anesthesia team are critical to this technique. Continuous patient monitoring and communication between surgeon and anesthesiologist allow for the safety and success of the procedure.

The appropriate level of conscious sedation confers several advantages. The surgeon is provided feedback via painful stimuli if there is any irritation of neural elements. The absence of general anesthetics enables a swift post-operative recovery, with relatively low incidence of amnesia, vertigo, nausea, dysphagia, or other adverse effects that may delay recovery, functional rehabilitation, and discharge.

Additional medications administered peri-operatively include pre-operative ondansetron and glycopyrrolate to limit intra-operative emesis. This has been a relatively recent addition to the regimen after two cases of intra-operative emesis that resulted in conversion to general endotracheal anesthesia (GETA). Oxymetazoline spray is also administered pre-operatively to avoid epistaxis, after this was the cause of one intra-operative conversion to GETA. Regarding analgesics, local liposomal bupivacaine is administered to subcutaneous tissue and paraspinal musculature during the procedure for pain control both intra- and post-operatively.

Surgical Technique

Patients are positioned prone on a Jackson table with the abdomen free to reduce intra-abdominal and central venous pressure. The arms are extended in the "superman" position. Kambin's triangle, the anatomical space comprising the traversing nerve root, exiting nerve root, and superior aspect of the caudal vertebra at a given level, is approached with a spinal needle and nitinol wire. This is completed on the side of the more significant pathology at the target level under

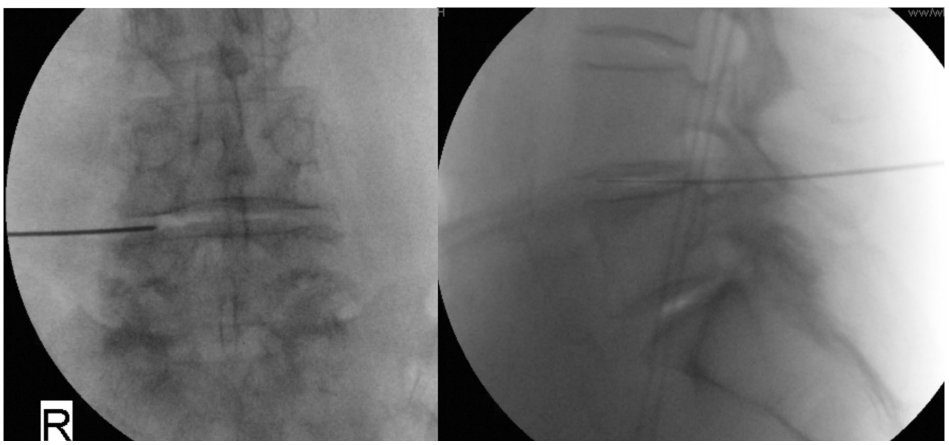

Fig. 1: Fluoroscopic images confirming intra-distal placement of a nitinol wire via a transforaminal approach at the target level.

fluoroscopic guidance (Fig. 1). Successive cannulated dilators allow for the introduction of an 8-mm working cannula through which both the endoscope and instruments may be simultaneously passed (Fig. 2). This allows for an entirely uniportal technique. The endoscope used has a 6.3-mm outer diameter, a 3.7-mm working channel, and a 30° viewing angle; it is initially inserted through this cannula for visualization of the disc space and of the traversing and exiting nerve roots.

Nerve roots are decompressed using pathology-specific endoscopic instruments, including pituitary rongeurs, curettes, micro-osteotomes, high-speed drills, and bipolar electrocautery. The disc space is similarly cleared of disc material, and adjacent endplates are prepared for bony fusion (Fig. 3). A high-speed drill equipped with a stainless-steel brush provides effective removal of residual disc material and cartilaginous endplate. A silicone balloon catheter filled with radiopaque medium allows for fluoroscopic assessment of the full extent of the discectomy and defines the location of the residual cartilaginous endplate (Fig. 4). Further endplate preparation may then be carried out, if necessary. This portion of the technique has been modified since initial adoption, after two early cases of post-operative interbody cage migration.

After adequate endplate preparation has been confirmed, 2.1 mg of recombinant human bone morphogenetic protein–2 is placed into the anterior disc space. Pre-treatment with radiopaque medium allows for fluoroscopic confirmation of placement in the desired location. A 22- or 25-mm OptiMesh (Spineology, St. Paul, MN, USA) expandable bone-graft containment mesh is then positioned in the disc space and filled with pre-machined allograft in situ. Appropriate placement and expansion allow for re-establishment of disc space height, additional indirect neural element decompression, and correction of any concomitant spondylolisthesis. It is worth noting that use of the endoscope precludes the need for any formal surgical approach, preserving all paraspinal musculature and bony architecture typically sacrificed for disc space access. It also allows for direct visualization of the foramen disc space, which facilitates accurate and thorough nerve root decompression and endplate preparation.

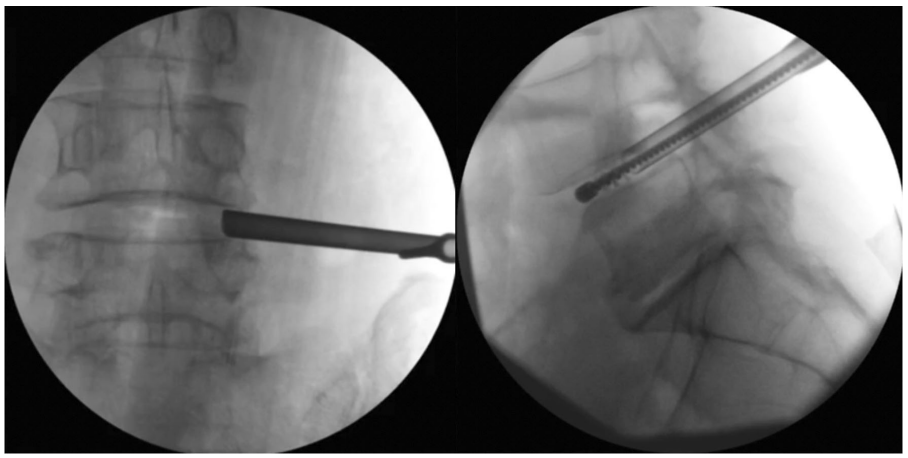

Fig. 2: Fluoroscopic images showing the 8-mm working portal placed transforaminally (*left*) and the use of the portal for endplate preparation via stainless-steel brush (*right*).

Pedicle screws are subsequently placed percutaneously. The paraspinal musculature within each of the four planned screw tracts are first injected with 20 mL of liposomal bupivacaine diluted 1:2 to 40 mL total volume. Anteroposterior fluoroscopic guidance allows for placement of trephine needles in the appropriate position and trajectory through these tracts. A guidewire is placed into each trephine needle, allowing for the placement of a cannulated awl and then a tap into the respective pedicles. Six or 7 mm pedicle screws are then placed; bilateral connecting rods are inserted subfascially; and set screws are placed to secure the construct. A total of five incisions are then closed with subcuticular sutures.

Results

Critical analysis of the first 100 such procedures performed by the senior author at a single institution demonstrate overall positive results with regard to clinical outcome, complication rate, and overall reduction in peri-operative morbidity. These results were previously reported [7], and we summarize them here. Consideration of awake endoscopic MIS TLIF was based on criteria including diagnosis of degenerative disc disease with grade I or II spondylolisthesis, as well as evidence of symptomatic spinal stenosis or focal nerve impingement at the same level. The average age of this cohort was 66 years. Of the 100 patients, 84 underwent procedures on a single level, with an average operative time of 84.5 ± 21.7 min, and average blood loss of 65.4 ± 76.6 mL; 16 patients underwent two-level fusions, with an average operative time of 128.1 ± 48.6 min, and average blood loss of 74.7 ± 33.6 mL; 77% of fusions were at L4–L5. Average length of stay was 1.4 ± 1 days.

Four cases in this series were converted to GETA intra-operatively due to emesis (2), epistaxis (1), and severe anxiety (1). After collective decision making among the surgical and anesthesia teams, all cases were completed in the same operative event after successful conversion to GETA. These episodes have prompted relatively simple adjustments to our peri-operative medication

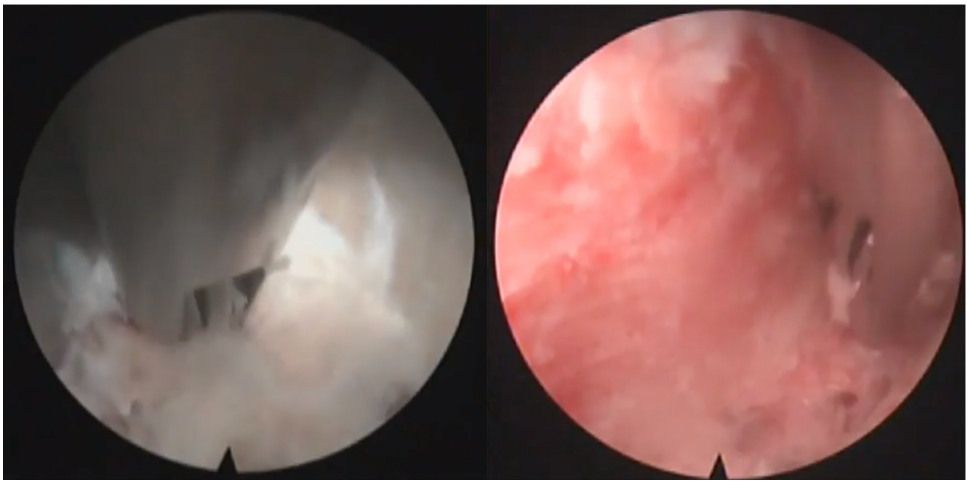

Fig. 3: Endoscopic visualization of initial discectomy (*left*) and final endplate preparation (*right*).

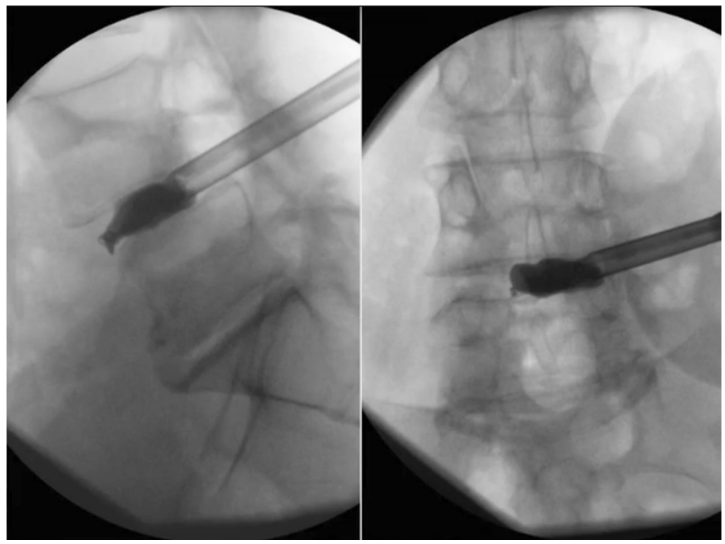

Fig. 4: Radiopaque balloon catheter inflation in the interbody space allows for radiographic evaluation of discectomy and endplate preparation.

protocol that have eliminated subsequent incidence. Regardless, careful pre-operative discussion with the patient as well as our dedicated and vigilant anesthesia team regarding the potential risk of conversion to GETA remains a mainstay of our practice.

At a minimum of 1-year follow up, there have been no cases of hardware failure or pseudarthrosis, with all patients demonstrating contiguous, radiopaque interbody arthrodesis, with no evidence of motion at the involved segment on anteroposterior, lateral, flexion, and extension radiographs. Four patients died due to causes unrelated to the described surgical intervention. Oswestry Disability Index (ODI) data was available for 82% of surviving patients. Average post-operative ODI (17.2 ± 16.9) was significantly improved from pre-operative measures (25.6 ± 15.3; $p = 0.000001$). Complications included interbody cage migration (2), vertebral osteomyelitis (1), and endplate fracture (1). Three of these complications occurred within the first 50 performed cases.

Discussion

In the experience of the senior author at a single institution, awake endoscopic TLIF provides several distinct advantages over traditional MIS and open techniques for single-level fusion. When compared with traditional MIS TLIF performed by the same surgeon, endoscopic TLIF had significantly shorter operative time, shorter post-operative length of stay, lower rates of nonroutine discharge, lower rates of complications, and reduced overall cost of acute hospitalization in a small series [13]. The reduced length of stay has been largely influenced by the mitigation in post-operative pain that this procedure offers. Along with the relative elimination of muscular dissection required by this approach, patients are subsequently able to embark on a more rapid return to functional status and comfort level permissive of discharge.

Over the course of the first 100 cases performed and beyond, several key adaptations have been made to target enhanced outcomes and patient experience. As described, our pre-operative medication protocol now includes ondansetron and glycopyrrolate, plus oxymetazoline spray, to reduce the incidence of intra-operative emesis and epistaxis, respectively. These additions were prompted by several early incidents of requisite conversion from sedation to GETA. Routine fluoroscopic evaluation of the targeted disc space to ensure adequate endplate preparation prior to fusion is now carried out after an early case of post-operative cage migration. The timing of local liposomal bupivacaine administration has been fine-tuned to just prior to percutaneous pedicle screw placement after ongoing critical monitoring of pain control in patients post-operatively. Of note, the majority of all described complications occurred in the early stages of implementation of this technique, likely indicating a learning curve.

Regular and rigorous evaluation of results and communication among all members of the dedicated surgical and anesthesia teams has been a mainstay of this technique, which continues to evolve and improve. Ongoing study at our institution will characterize outcomes in a larger sample size as the use of this technique continues, with the hope of describing the feasibility of its widespread application and subsequent implications for outcomes and cost.

Compliance with Ethical Standards

Conflict of Interest: Alexander J. Butler, MD, and G. Damian Brusko, BS, declare that they have no conflicts of interest. Michael Y. Wang, MD, reports royalties from DePuy-Synthes Spine, Inc., Children's Hospital of Los Angeles, Springer Publishing, and Quality Medical Publishing; personal fees as a consultant from DePuy-Synthes Spine, Inc., JoiMax USA, K2M, and Aesculap Spine; advisory board membership for Vallum; stock in Spinicity and Innovative Surgical Devices; and grants from the US Department of Defense.

Human/Animal Rights: All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2013.

Informed Consent: Informed consent was waived from all patients for being included in this study.

Required Author Forms: Disclosure forms provided by the authors are available with the online version of this article.

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