Clinical Report

Biomechanical Comparison of Two Surgical Methods in Treating Stage IIb Lunate Necrosis

Chuan Li, Yong-Yue Su, Xiao-Shan Xu, Tian-Hua Zhou, Xin-Yu Fan and Yong-Qing Xu

Department of Orthopedic Surgery, Kunming General Hospital, Kunming, China
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Abstract: This study aims to determine the biomechanical changes and basis for treatment using two surgical methods (scaphotrapeziotrapezoid [STT] fusion and capitoscapoid [CS] fusion) for stage IIb lunate necrosis. Eighteen fresh frozen upper extremities of adult cadavers were randomly divided into three groups. In group A, only the radioscapoid and radiolunate spaces were exposed to place pressure sensors. Groups B and C underwent STT and CS fusion, respectively. The advanced I-scan pressure measurement system was used. Piezoelectric films were placed at the radioscapoid and radiolunate spaces of wrist joints, and connected to the computerized I-scan system, which was then connected to a biaxial hydraulic material testing system (MTS). Pressure (up to 100 N) was applied to the wrist in inferior neutral position at a 10 N/s compression rate. The pressure distribution, pressure loading, and other data on the radioscapoid and radiolunate articular surfaces for each sample were dynamically recorded and analyzed. After application of pressure with the wrist in neutral position, the radioscapoid and radiolunate pressure values of the normal wrist group A were 41.39 ± 6.93 N/cm² and 39.22 ± 6.61 N/cm², respectively; those of the STT arthrodesis group B were 83.89 ± 11.27 N/cm² and 22.55 ± 11.27 N/cm²; and those of the SC arthrodesis group C were 86.45 ± 8.10 N/cm² and 34.11 ± 8.10 N/cm². Compared with CS fusion, STT fusion surgery has much greater value in preventing rotatory semidislocation of the scaphoid bone, as well as in maintaining the stability of the wrist. It is the preferred surgical treatment for stage IIb lunate necrosis.

Key words: Wrist joint, Lunate necrosis, Biomechanics, Scaphotrapeziotrapezoid fusion, Capitoscapoid fusion

Introduction

Lunate necrosis is the most common carpal ischemic necrotic disease. Lunate aseptic necrosis is also known as Kienbock's disease¹⁾. The staging of Kienbock's disease is the basis for the development of treatment programs. Currently, the Lichtman classification is the most widely used staging method^{2,3)}, and divides Kienbock's disease into four stages. Among these, stage IIb is the most serious, and fractures progress to sclerosis and/or collapse⁴⁾. Meanwhile, this is accompanied by rotatory dislocation of the scaphoid bone. Surgery for stage IIb varies, and commonly used treatments include necrotic lunate revascularization, ulnar shortening surgery, and partial carpal fusion⁵⁻⁷⁾. Studies showed that scaphotrapeziotrapezoid (STT)⁸⁾ fusion and capitoscapoid (CS)^{9,10)} partial fusion surgery could effectively eliminate interaction between the scaphoid and distal carpal bones, and were considered to be an effective means of reducing lunate loading and the rate of lunate necrosis. The present study used fresh frozen upper extremities of adult cadavers to compare biomechanical

changes using STT fusion and CS fusion for stage IIb lunate necrosis, to determine a more appropriate surgical approach.

Materials and Methods

Specimens

Eighteen fresh frozen upper extremities of adult cadavers aged 16 to 60 years, with a mean age of 31, were selected; the gender and side selected were not considered. Before the experiment, all specimens underwent X-ray examination to confirm that the wrists were intact, and without injury, cancer, abnormal relaxation, or movement limitations. After thawing, the specimens were amputated at the distal third of the forearm, the distal end was amputated from the metacarpophalangeal joints, and the distal and proximal specimen ends were embedded with self-curing denture powder (Fig. 1). The specimens were stored at -40°C for elective surgery. This study was conducted in accordance with the declaration of Helsinki and approval from the Ethics Committee of Kunming General Hospital (No. 2011017). Written informed consent was obtained from all participants.

Grouping

The 18 specimens were randomly divided into A, B, and C

Corresponding to: Dr. Yong-Qing Xu, Department of Orthopedic Surgery, Kunming General Hospital, No. 212 Daguan Road, Kunming 650032, China; Tel: +86 0871 64774655; Fax: +86 0871 64774655; E-mail: yongqingxucn@126.com

Figure 1. Specimens of upper extremity with the distal and proximal end embedded with the self-curing denture powder.

Figure 2. X-ray films of normal positions of these 3 groups after the operation. A: The A group; B: The STT fusion group; C: The CS fusion group.

and dorsal side of the radial malleolus in specimens of all three groups. The extensor retinaculum was then cut along the tendon of the extensor hallucis longus. The wrist joint capsule between the radial-side long and short extensor tendons was cut, exposing the dorsal side of the scaphoid bone.

In group A, only the radioscaphoid and radiolunate spaces were exposed layer by layer to place the pressure sensors (Fig. 2A). In group B, the articular surfaces between the trapezium and scaphoid bones, between the trapezoid and scaphoid bones, and between the trapezium and trapezoid bone were exposed. A 2.0 mm diameter Kirschner needle was used to penetrate these three articular surfaces and fix three bones successively (Fig. 2B). In group C, the articular surfaces of the scaphoid and capital bones were exposed, and two Kirschner needles were used to penetrate the articular surface for the fixation of these bones (Fig. 2C). The

Figure 3. Placement of pressure sensor. A: The pressure sensors with appropriate model were placed among the articular surfaces; B: The skin-edge outer suture and slipknot fixation to fix the pressure sensor.

groups, with six specimens in each group. Group A was the normal wrist, B was the STT fusion group, and C was the CS fusion group.

Surgical methods

A 3.5-4.0 cm transverse incision was made at the distal end

wrists of these three groups were moved after the operation to ensure no displacement among the fused and fixed bones.

Pressure test

The radioscaphoid and radiolunate joint spaces were exposed

Figure 4. The specimens were fixed onto the chassis and top plate of MTS machine, then connected with the calibrated I-scan pressure measurement system

in the pre-embedded specimens, and pressure sensors were placed on the articular surfaces, followed by skin-edge outer suture and slipknot fixation (Fig. 3). The proximal and distal ends of specimens were fixed onto the chassis and top plate of a high accuracy biological material test system (MTS) instrument (3510, ElectroForce, USA), then connected to a calibrated I-scan pressure measurement system (Tekscan, USA) (Fig. 4). The chassis was then adjusted to control the flexion and extension angles of the wrist. Referring to Palmer-defined wrist functional ranges⁽¹⁾, the chassis was adjusted to place the wrist in the inferior neutral position for the pressure test. A 0.1 mm thick flexible film grid-like tactile pressure sensor was used to perform static and dynamic measurements for the pressure distributions at any contact surface, and the outline of pressure distribution and various data could be shown as real-time visual 2-dimensional and 3-dimensional color images (Fig. 5). The entire measurement procedure was recorded and stored. During the test, pressures were added from both the proximal and distal ends simultaneously, starting from 0 N and increasing to 100 N at a rate of 10 N/s, and maintained for 20 s. The I-scan system was used to dynamically record the average values at the radioscapoid and radiolunate joints of each group during the 20-s fixation. The three groups all used average values at pressure-stable regions at the radioscapoid and radiolunate joints as the reference values for each group, when the specimens were in the inferior neutral position.

Figure 5. The pressure distributions on radioscapoid articular surface displayed by real-time visual 2D and 3D color images of I-scan system.

Statistical analysis

All data were analyzed using SPSS 17.0 software for statistical analysis. The data showed a normal distribution, and were expressed as mean $\pm$ standard deviation (SD). After homogeneity of variance testing, the multiple-group comparison used one-way analysis of variance (ANOVA). Pairwise comparison among multiple groups used the Student–Newman–Keuls (SNK) method, and the two independent-sample t-test was performed. $P < 0.05$ was considered statistically significant.

Results

The pressure testing of the three groups was successfully completed. During the testing process, the wrists of each group were intact and uninjured, and the Kirschner wire showed no slippage, breakage, or other abnormality.

In group A, the average load per unit area at the radioscapoid and radiolunate joint spaces was uniform, with no statistically significant difference ($P > 0.05$). In groups B and C, the average load at the radioscapoid joint spaces was significantly greater than that at the radiolunate joint spaces ($P < 0.05$).

The average load per unit area at the radiolunate joint space of group A was significantly greater than that of groups B and C ($P < 0.05$), while the load at the radioscapoid joint space of group A was significantly less than that of groups B and C ($P < 0.05$). The average load per unit area at the radiolunate joint space of group B was significantly less than that of group C ($P < 0.05$), while the load at the radioscapoid joint space of group B was slightly less than that of group C ($P > 0.05$) (Table 1).

Table 1. Average Loadings on Per Unit area of the Radioscapoid and Radiolunate Joint Spaces when the Wrist was in the Neutral Position ($\bar{x} \pm s$, N/cm²)

Neutral Position	Radiolunate Joint Space	Radioscapoid Joint Space
A group	39.22 $\pm$ 6.61	41.39 $\pm$ 6.93
B group	22.55 $\pm$ 11.27	83.89 $\pm$ 11.27
C group	34.11 $\pm$ 8.10	86.45 $\pm$ 8.10
F	37.653	42.318
<i>P</i>	< 0.01	< 0.01

Note: The A group was the normal wrist group; The B group was the STT fusion group; The C group was the CS fusion group.

Discussion

Although scholars worldwide had studied Kienbock's disease for many years, the natural history and etiology remained unclear. Some studies found that ulnar negative variance was significantly correlated with Kienbock's disease^{2,12,13}). However, other reports stated that ulnar variance had no correlation with Kienbock's disease^{14,15}). Moreover, the occurrence rates of ulnar negative variance in Kienbock's disease patients and the normal population were the same^{12,16}). Han et al.¹⁷) described the relationships between lunate morphology and ulnar length, and thought that the trabecular structures of lunate bones with different morphologies were different; thus, the weakest trabecular structure would be most prone to fatigue and stress fractures with loading, which tended to lead to bone necrosis^{12,17,18}). Reduced blood supply to the lunate bone is a major contributor to Kienbock's disease. A perilunate venous return disorder could cause inner lunate pressure to increase, and the blood supply to the lunate bone would be reduced, which ultimately would result in necrosis. Some studies found that the aseptic necrotic lunate bone exhibited increased inner bone pressure, compared with normal lunate bone. Pichler and Putz¹⁹) studied reflux in the lunate veins in cadaveric specimens and found many dense and thickened vascular plexuses on the surface of the volar and dorsal periosteum. They suggested that these plexuses might be the location of venous breakage and blockage, probably as a result of systemic and local secondary pressure factors.

The staging of Kienbock's disease is the basis for developing treatment programs. Currently, the Lichtman classification is the most widely used staging system²). Recent literature reported that early detection of lunate lesions and appropriate treatment for different stages could effectively ameliorate necrosis²⁰). X-rays of stage IIIb show lunate collapse combined with displacement of the capital bone towards the proximal end. The scaphoid bone shows a high degree of flexion, and the scapholunate angles in some cases are significantly increased. The treatment of stage IIIb Kienbock's disease varies, and common treatment methods include ulnar shortening surgery and partial carpal fusion. In the past few years, it was found that many types of limited wrist arthrodesis could help treat Kienbock's disease, and partial surgical methods such as STT or CS fusion could effectively eliminate interaction between the scaphoid and distal carpal bones. Therefore, these were considered to be effective means of reducing lunate loading^{8-10,13}). Van den Dungen et al.²¹) and Tatebe et al.²²) thought that these two surgeries played a role in stabilizing the wrist, as well as reducing lunate loading, and were the best options for treatment of Kienbock's disease. In short, the core principles of various treatment strategies for different stages included the reduction of lunate loading, thereby facilitating blood supply to the ischemic lunate bone, as well as rescue measures such as symptomatic treatment.

This study investigated the biomechanical changes resulting from STT and CS fusion in treatment of stage IIIb lunate necrosis. Lichtman stage IIIb is the most severe stage of Kienbock's disease. The lunate bone progresses to fracture and/or collapse, and is accompanied by rotatory dislocation of the scaphoid bone. STT and CS fusion were designed to reduce lunate loading, correct the scapholunate angle, and reduce carpal collapse, thus alleviating the symptoms of lunate necrosis. This study found that loading at the radiolunate and radioscapoid joints in group A was relatively stable and uniform; however, after fusion surgery, loading at the radioscapoid joints of groups B and C was significantly increased, but significantly reduced at the radiolunate joint. The forces on the wrists of groups B and C were mainly concentrated onto the STT and CS fusion body; thus, the force on the damaged lunate bone in stage IIIb was significantly alleviated, and the force in group B was decreased even more than in group C. This indicated that STT fusion surgery was much more effective in reducing lunate loading.

In conclusion, STT and CS fusion can effectively reduce lunate loading in stage IIIb of Kienbock's disease. STT fusion has much greater value in preventing rotatory semidislocation of the scaphoid bone, as well as maintaining the stability of the wrist. It is the preferred surgical treatment for stage IIIb lunate necrosis.

Conflict of Interest

All authors have no COI regarding this paper.

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