Biomechanical Stability of a Fixed-Angle Volar Plate Versus Fragment-Specific Fixation System: Cyclic Testing in a C2-Type Distal Radius Cadaver Fracture Model

Kenneth F. Taylor, MD, Brent G. Parks, MSc, Keith A. Segalman, MD

From the Orthopaedic Surgery Service, Tripler Army Medical Center, Honolulu, HI; and the Raymond M. Curtis National Hand Center, Baltimore, MD.

Purpose: To compare the biomechanical stability of 2 recently introduced fixation systems in an intra-articular, dorsal comminution distal radius fracture model.

Methods: AO/ASIF type C2 fractures were simulated in 10 matched pairs of fresh-frozen cadaveric arms randomized between fixed-angle volar plate and fragment-specific fixation systems. Specimens were loaded in extension cyclically for 2,000 repetitions followed by a single cycle to failure. Initial, intermediate, and final stiffness values and failure load values were obtained and compared.

Results: Both systems were able to sustain physiologic cyclic loading. The fragment-specific system was significantly stiffer than the fixed-angle volar plate system for the ulnar segment in both the precycle and postcycle values. No other comparisons were significant with respect to stiffness. No significant difference in load to failure was found between the systems with respect to ulnar, radial, or overall fragment displacement.

Conclusions: Both fixed-angle volar plate and fragment-specific fixation systems performed comparably in a simulated early postoperative motion protocol. Fragment-specific fixation had improved stiffness characteristics only with respect to the smaller ulnar-sided fragment. (J Hand Surg 2006;31A:373–381. Copyright © 2006 by the American Society for Surgery of the Hand.)

Key words: Distal radius fracture, fixed-angle volar plate, fragment-specific fixation.

Numerous techniques exist for obtaining and maintaining reduction of intra-articular fractures of the distal radius. These include closed reduction and cast immobilization, percutaneous pin fixation, external fixation, open reduction and internal fixation (ORIF) with either dorsal or volar plating systems, or a combination of these techniques. The objective of each technique is stable fixation with the goal of resuming early functional activities. Each fixation technique offers its own set of advantages and potential disadvantages. Recent trends in fixation have emphasized rigid stability capable of withstanding forces generated during early wrist range of motion and strengthening. Putnam et al\(^1\) determined that an extrinsic grip force of only 10 N generates 26.3 N of axial force through the distal radius. This is important because forces generated during early rehabilitation should not exceed one half of the fixation failure forces reported for traditional fixation systems. Biomechanical testing has shown fixed-angle volar locking plate fixation to be superior to traditional dorsal plating techniques.\(^2\) Similarly fragment-specific internal fixation has been shown to be more rigid than augmented external fixation.\(^3\) Our hypothesis was that a significant difference in biomechanical stability exists between fragment-specific and fixed-angle volar plate fixation systems.

Materials and Methods
Ten matched pairs of fresh-frozen cadaveric forearms were obtained from the Maryland state anatomy...
board. The average age of the specimens was 77 years (range, 49–101 y). All soft tissues were dissected from the specimens except for the interosseous membrane, wrist capsuloligamentous structures, and transverse metacarpal ligament. Fluoroscopic images were obtained to rule out a previous fracture or pathologic condition. One radius from each matched pair was assigned randomly to 1 of the 2 groups. A standardized 3-part intra-articular fracture with dorsal comminution (AO/ASIF type C2) was simulated on all specimens by performing sequential osteotomies with an oscillating saw. A 1-cm transverse dorsal wedge osteotomy, centered 2 cm proximal to the articular surface of the lunate fossa, was made. A second sagittal split osteotomy was performed between the scaphoid and lunate fossa, creating an unstable intra-articular fracture with both a radial styloid and ulnar-sided fracture fragment. One group was stabilized with fixed-angle volar plates with smooth subchondral distal pegs (Hand Innovations, Miami, FL) (Fig 1). The second group was fixed with radial and ulnar pin plates (TriMed, Inc., Valencia, CA) (Fig. 2). Fluoroscopic imaging was used to obtain facet lateral views in every volar plate specimen at several intervals to include placement of the guidewire in the dorsal ulnar fragment and after placement of the smooth pegs themselves. This ensured that the pegs were as close to the subchondral plate as possible without entering the joint space. Likewise fluoroscopic images were used in the fragment-specific group to ensure proper starting point locations for K-wire fixation of the distal fragments. Hard copies of these images were printed but are not of sufficient photographic quality to be included in the publication.

Once prepared the specimens were mounted in a servohydraulic load frame (Mini Bionics MTS Systems, Eden Prairie, MN) in a manner that allowed extension loading of the wrist (Fig. 3).

Differential variable reluctance transducers (Microstrain, Williston, VT) were mounted across the simulated fracture sites dorsally, 1 across the radial side and the other across the ulnar side of the radius. These instruments were used to measure the gap closing of the simulated fracture site. Cyclic loading was applied to the palmar aspect of the hand from 0

---

**Figure 1.** Radiographs of a specimen stabilized with a fixed-angle volar plate system. (A) Posteroanterior and (B) lateral views.

**Figure 2.** Radiographs of a specimen fixed with a fragment-specific system. (A) Posteroanterior and (B) lateral views.

**Figure 3.** A specimen mounted in a system for cyclic loading (MTS) followed by load to failure in wrist extension.
to 50 N at a rate of 1 Hz for 2,000 cycles. This approximates the estimated physiologic preload based on the cross-sectional area of muscles crossing the wrist joint.\(^4\) Load and gap closing data were recorded on a personal computer at every 100 cycles to calculate prefailure stiffness (N/mm). Load versus gap closing curves were generated for each of the differential variable reluctance transducers. Initial, midpoint (1,000 cycles), and final stiffness values were obtained from the initial linear portion of the load versus gap deformation curves for each sample. After this the specimens were loaded by a single cycle to failure at a rate of 10 mm/s. Load to failure was determined for each specimen and was defined as the load required to create a 2.0-mm gap closure across the simulated fracture. Data from the 2 groups were compared. A Student \(t\) test analysis was used to determine if any observed differences were significant (\(p \leq .05\)).

**Results**

One specimen from each group failed catastrophically at approximately 300 cycles. The specimens were not from the same matched pair. In the case of the fixed-angle volar plate system failure occurred when the smooth pegs pulled out from the distal fracture fragments (Fig 4). In the fragment-specific fixation system failure occurred when the retrograde K-wires also pulled out from the distal fragments (Fig. 5). The remaining 18 specimens completed cyclic loading and subsequent load to failure.

A summary of stiffness measurements is provided in Tables 1 and 2. Initial, or precycle, stiffness was measured with the first cycle. Intermediate values were those measured at 1,000 cycles. Final, or postcycle, stiffness was measured at 2,000 cycles. A significant difference in stiffness was observed between the fragment-specific and fixed-angle volar plate systems for the ulnar-sided segment in both the initial (218.8 ± 130.9 N/mm vs 78.9 ± 36.8 N/mm, respectively) and final (355.5 ± 149.7 N/mm vs 142 ± 104.5 N/mm, respectively) values (\(p \leq .05\)). With respect to the fixed-angle volar plate there was a statistically significant difference in initial stiffness of the radial- versus ulnar-sided fragments (\(p = .04\)). This was no longer apparent when final stiffness values were compared. No other comparisons were significant with respect to stiffness (Table 3). No significant difference was found between failure loads for the fragment-specific or fixed-angle volar plate systems with respect to ulnar, radial, or overall fragment displacement (Table 4).

**Discussion**

Distal radius fractures account for 15% to 20% of all reported fractures. They represent the most common fracture location of the upper extremity, with approximately 50% involving the articular surface.\(^5\) Recent trends in distal radius fracture fixation emphasize anatomic reduction and rigid fixation allowing early mobilization and return to functional activities. This, coupled with greater patient demands, has stimulated a closer look at fixation systems. Historically wrists were thought to do well with less-than-perfect fixation.\(^6\) More recently Catalano et al\(^7\) described long-term results in young adults with displaced intra-articular fractures after ORIF. They described good to excellent functional outcomes even in those patients with radiographic evidence of osteoarthritis. There was a significant difference in strength and motion between the injured and uninjured wrists but only wrist flexion correlated with degree of residual articular displacement. There was a strong correla-
tion between residual articular incongruity and the development of osteoarthrosis. McQueen et al found no difference between ORIF with bone graft, plaster immobilization, or external fixation with respect to functional outcome. They did state that ORIF was more effective in restoring dorsal or volar angulation. This series excluded displaced intra-articular fractures requiring open reduction. Other studies have strengthened the case further for anatomic restoration of the articular surface. In a retrospective review of displaced intra-articular fractures treated by ORIF or external fixation Trumble et al found decreased articular step-off, articular gap, and radial shortening to correlate strongly with better outcome whereas radial or dorsal tilt did not correlate well with outcome. Gliatis et al treated adults younger than 50 years with various fixation methods and examined the results. Residual intra-articular step-off was associated with decreased wrist mobility and difficulty with fine motor tasks. More than 10° of dorsal tilt was associated with difficulties with activities of daily living and work. This may be explained by the earlier work by Short et al who found that a 20° change in sagittal tilt substantially alters load patterns across the wrist, manifested by increased weight bearing through the ulna. Within the radius increased loads are seen across the dorsal aspect of the radiocapitate joint.

The fixation system used is dictated by the fracture pattern as much as by the surgeon’s experience. Each has its potential role with inherent benefits and pitfalls. A lengthy discussion of each technique is beyond the scope of this study; nonetheless, common themes deserve mention. The positive effect of early passive motion on articular cartilage in an animal model is well established. With respect to repair of hyaline cartilage Salter et al showed significant improvement over immobilization and intermittent motion, of which there was little difference between the latter 2. This admittedly was in a non-weight-bearing adolescent rabbit model, which has limited applicability to the human wrist. The benefit of early range-of-motion exercises more likely relates to its effect on the restoration of range of motion with resulting earlier return to activities of daily living and work.

Most fracture fixation techniques used today require some form of immobilization. Closed reduction and cast immobilization has been found to result in a 40% decrease in forearm pronation, a 50% percent reduction in arc of flexion/extension and radial/ulnar deviation, and a 24% reduction in grip strength when measured within 48 hours of cast removal. Several treatment options have been introduced to counteract the effect of immobilization on joint stiffness. In a large series of both displaced and minimally displaced Colles’ fractures, Dias et al found that early mobilization with a cast modified to allow active wrist flexion led to an earlier functional recovery. Some degree of bony deformity recurred irrespective

| Table 1. Summary of Stiffness Values of Radial-Sided Fragments (N/mm) |
|------------------------|------------------------|------------------------|
|                        | Initial | Intermediate | Final       | Initial | Intermediate | Final       |
| Mean                   | 184.70  | 439.63       | 520.28      | 236.93  | 268.87       | 278.46      |
| Minimum                | 44.50   | 99.00        | 115.00      | 24.00   | 40.00        | 37.40       |
| Maximum                | 286.00  | 1075.00      | 1781.10     | 670.90  | 752.00       | 1021.50     |
| SD                     | 83.48   | 356.99       | 551.99      | 220.46  | 303.89       | 343.20      |

SE, standard error.

| Table 2. Summary of Stiffness Values of Ulnar-Sided Fragments (N/mm) |
|------------------------|------------------------|------------------------|
|                        | Initial | Intermediate | Final       | Initial | Intermediate | Final       |
| Mean                   | 218.83  | 242.48       | 355.49      | 78.94   | 120.13       | 141.97      |
| Minimum                | 62.00   | 156.00       | 182.10      | 39.90   | 41.90        | 37.70       |
| Maximum                | 442.00  | 341.00       | 610.20      | 145.40  | 255.30       | 333.70      |
| SE                     | 49.48   | 27.23        | 52.94       | 11.62   | 25.55        | 33.04       |
| SD                     | 130.91  | 77.03        | 149.73      | 36.75   | 80.79        | 104.49      |

Initial (p = .04) and final (p = .003) stiffness comparisons between fragment-specific and fixed-angle volar plate systems were statistically significant.

SE, standard error.
of the treatment method. Dynamic external fixators have been developed in an attempt to reduce the effect of immobilization but have resulted in varying degrees of loss of reduction. Nonbridging external fixators also have been used but their use may be limited by the amount of volar cortex available for pin purchase. Traditional dorsal plating of the distal radius has the potential for rigid fixation, thus avoiding the prolonged immobilization associated with external fixation. Delayed complications may arise, though, because of tendon attrition over relatively prominent implants. The use of volar plating may help avoid this pitfall.

Dorsally displaced intra-articular distal radius fractures (AO/ASIF type A2–C3) can be managed effectively with volar plating. Fixed-angle volar plate systems have shown encouraging early clinical results. These systems have compared favorably with traditional dorsal or volar plates, with resistance to axial loading approaching that of the distal radius in 1 study. In the particular implant used in this study proximal plate fixation is performed with 3.5-mm cortical screws. Distal fixation is performed through 2.0-mm subchondral support pegs that thread (lock) into the plate. The implant, which functions as an internal buttress, does not require screw fixation of the distal fragments, which may in turn reduce the occurrence of screw toggling and subsequent loosening. The option for threaded distal pegs does exist, as does a second row for additional fixation of markedly comminuted fragments. Volar placement takes advantage of the healing capacity of the distal radius by maintaining the vascularity of dorsal comminuted fragments. Wrist range of motion generally can begin at approximately 3 to 5 days after surgery, although this is prescribed infrequently. A removable wrist splint typically is used for 3 weeks. Early postoperative fracture fragment displacement may be attributed to settling of the distal fragment until it comes in direct contact with the subchondral plate. Therefore far distal placement of the subchondral pegs is necessary.

Fragment-specific fixation requires an individualized approach to the fracture pattern using low-profile implants. Orthogonal placement of the components increases stability. Distal fixation is through 1.4-mm (0.045-in) wires secured to a thin plate. Proximal plate fixation is achieved with 2.0-mm cortical screws. Additional fixation options exist through the use of wire forms and clips. Mobilization generally is encouraged by postoperative days 4 to 7. Swigart and Wolfe reported good to excellent results in a limited case series using early postoperative mobilization. A prospective series by Konrath and Bahler showed excellent clinical and radiographic results. Their postoperative restrictions included avoidance of lifting the weight of a gallon of milk, pushing up from a chair, and contact sports. Unrestricted activities ensued at 6 weeks. In a direct cadaveric comparison Dodds et al found this method

<table>
<thead>
<tr>
<th>System</th>
<th>Fragment p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragment-specific system</td>
<td></td>
</tr>
<tr>
<td>Radial-sided fragment initial versus final</td>
<td>.130</td>
</tr>
<tr>
<td>Ulnar-sided fragment initial versus final</td>
<td>.950</td>
</tr>
<tr>
<td>Radial-sided fragment versus ulnar-sided fragment, initial</td>
<td>.230</td>
</tr>
<tr>
<td>Radial-sided fragment versus ulnar-sided fragment, final</td>
<td>.420</td>
</tr>
<tr>
<td>Fixed-angle volar plate system</td>
<td></td>
</tr>
<tr>
<td>Radial-sided fragment initial versus final</td>
<td>.680</td>
</tr>
<tr>
<td>Ulnar-sided fragment initial versus final</td>
<td>.110</td>
</tr>
<tr>
<td>Radial-sided fragment versus ulnar-sided fragment, initial</td>
<td>.040*</td>
</tr>
<tr>
<td>Radial-sided fragment versus ulnar-sided fragment, final</td>
<td>.240</td>
</tr>
<tr>
<td>Fragment-specific versus locking volar plate</td>
<td></td>
</tr>
<tr>
<td>Radial-sided fragment initial</td>
<td>.510</td>
</tr>
<tr>
<td>Radial-sided fragment final</td>
<td>.260</td>
</tr>
<tr>
<td>Ulnar-sided fragment initial</td>
<td>.040*</td>
</tr>
<tr>
<td>Ulnar-sided fragment final</td>
<td>.003*</td>
</tr>
</tbody>
</table>

*Statistically significant (p < .05).
of fixation to be more rigid than augmented external fixation.

Both fixed-angle volar plate and fragment-specific fixation systems claim to be sufficiently rigid to endure early postoperative mobilization. Previous studies of distal radius fracture fixation focus on load to failure, which simulates a single event such as a fall on an outstretched hand. We sought to establish a model of cyclic loading, to simulate early rehabilitation, and to determine subsequent loads to failure. This study represents a model of cyclic loading with a physiologic load encountered during rehabilitation.

In developing our model there were several considerations to be addressed. The first related to the material itself. Biomechanical studies of external fixation devices have used acrylic rods and wooden dowels. This might seem appropriate for mechanical analysis of the device itself but it would not assess the ability of the device to control specific fracture patterns. The model needed to be reproducible and clinically relevant. We chose a standardized 3-part intra-articular fracture with dorsal comminution (AO/ASIF type C2) for our analysis. With the use of an oscillating saw precise osteotomies ensured reproducibility. A 1-cm dorsal wedge osteotomy placed 2 cm proximal to the articular surface effectively simulated dorsal comminution without introducing the additional variable of distal radioulnar joint involvement.

Most previously reported studies directly loaded the radius in isolation. By preserving the capsuloligamentous restraints we ensured a more clinically relevant loading pattern across the carpus. Dodds et al also maintained the carpal ligamentous structures, pronator quadratus, and interosseous membrane. They took the additional step of loading their constructs through the extrinsic wrist tendons. This seemed unnecessary—if not overburdensome—for the purpose of our study.

The next consideration related to the positioning of the carpus and pattern of loading the wrist. Rikly and Regazzone described a 3-column distal forearm articulation system that comprised the scaphoid facet, lunate facet, and distal ulna. With the application of pressure-sensitive conductive rubber Hara et al described force distribution across the wrist joint. Force transmission patterns in the wrist neutral position consisted of 50% across the scaphoid fossa, 35% across the lunate fossa, and the remaining 15% across the triangular fibrocartilaginous complex. The scaphoid-to-lunate ratio was 1.7 in neutral, 2.9 in radial deviation, and 0.8 in ulnar deviation. There was no substantial difference with change of position in the flexion-extension plane. Naidu et al recognized that distal radius fractures usually fail by dorsal collapse and angulation, justifying a bending test in extension. Unlike our study, their study used specimens stripped of all soft tissues. A straight dorsal bending force may oversimplify the mechanism of injury. Saeki et al agreed that radial shortening and rotational displacement are difficult to model but reasonably may be thought to occur secondary to dorsal displacement.

In light of the claim by both systems that early mobilization would be well tolerated we decided to test fixation with cyclic loading before load to failure. This would simulate early rehabilitation followed by a fall on an outstretched hand. Our final consideration was to model physiologic loading through a clinically applicable model. Putnam et al determined that for a given extrinsic grip force, roughly 2.5 times that force is generated through the distal radial metaphysis. The wrist was positioned in extension with ulnar deviation during this analysis.

Several studies have sought to determine the magnitude of loading to be expected across the wrist during joint mobilization. Simpson et al tested external fixators mounted on wooden dowels under cyclic loads (25 cycles) between 10 and 50 N. They reasoned that although the magnitude of forces about the wrist joint previously had not been calculated accurately, an upper limit of 50 N appeared reasonable. Smith et al applied loads through tendons crossing the carpus based on their physiologic cross-sectional area and relative electromyographic activity in each wrist position. They determined the minimal loads required to produce maximal wrist deviation in each direction. Each was well within 50 N, with extension requiring 26.2 N. Ruby et al also modeled loads across the carpals based on physiologic cross-sectional area, with averages near 50 N. Since these studies were reported other studies have mod-
eled systems with physiologic preloading of 39.2 N, simulating resting muscle tone across the wrist, followed by 3 incremental increases to a maximum of 98 N. Our model of cyclic loading with 50 N in extension through a ligamentously intact carpus followed by incremental loading to failure differs from these other studies but is supported by the literature.

Overall in the current study both the fixed-angle volar plate and the fragment-specific systems performed well. With the exception of 1 specimen in each group both systems were able to withstand cyclic loading within the range of previously accepted physiologic loading encountered during early postoperative mobilization. The only significant differences that we found were on the smaller, ulnar-sided fragment. The initial stiffness values differed significantly for the fixed-angle volar plate and fragment-specific systems (p < .003). This can be extrapolated to the clinical setting in that the initial stiffness represents the stability of the construct immediately after surgery. The final difference in stiffness found in the current study also may be important in early rehabilitation. Interim stiffness values decreased between the initial and final values as one would expect.

Although not statistically significant the stiffness values of the ulnar and radial fragments each increased in both the fracture-specific and fixed-angle volar plate systems. For the fixed-angle volar plate system this likely was caused by settling of the subchondral plate onto the distal pegs. With respect to fragment-specific fixation a similar finding could be explained reasonably by a tension band–like effect of the pin plate fixation, especially with respect to the radial side. This is a potential topic of further investigation.

There was a difference in the ability of the volar plate to control the individual fragments. There was a statistically significant difference in initial stiffness of the radial- versus ulnar-sided fragments (p = .04). This was no longer apparent when final stiffness values were compared. Ultimate loads to failure across these fragments were not statistically significant. This observation is difficult to explain because it would appear that the fragments may have settled differentially but at this point this is purely conjecture. Although the failure loads favor the fragment-specific fixation system no significant difference was found (p > .050).

There are several possible criticisms of the technique used in this study. The first is the choice of fixation in the fixed-angle volar plate system. The practical answer to this is that the threaded pegs and double-row plates were not available when this study was completed. Although the larger-diameter smooth pegs might offer the strongest subchondral support it is possible that threaded screws could have offered additional stability by capturing comminuted fragments. Likewise the addition of fixation from the distal row might have had a beneficial effect because its use is recommended in the presence of extensive comminution or severe osteoporosis. Nonetheless in every specimen each fragment had 2 smooth pegs for distal fixation in concert with the more proximal cortical screw plate fixation. Likewise in the fragment-specific fixation each fragment had 2 K-wires in addition to pin plates. This question of choice of fixation lends itself to further investigation.

A second criticism might be in the fracture pattern used in this study. We selected this particular fracture pattern because it lent itself to either fixation system. We did not predict that it would prejudice results unfairly in favor of either the fixed-angle volar plate or fragment-specific fixation. We do agree that alternative fracture patterns may respond differently and we believe that this is an additional topic for further investigation.

A third criticism might refer to the probability that orthogonal fragment fixation rather than the implant itself provided a statistically significant difference in the stiffness of ulnar fragment fixation. To the extent to which we tested our specimens this too is plausible. The inherent stiffness of a thin pin plate most likely is less than that of the more stout volar plate. It is the intent of fragment-specific fixation to stabilize fragments in the more biomechanically favorable orthogonal orientation. By design this allows for lower-profile components. Our observation that radial-sided fixation did not show a significant difference might argue that it was not the orthogonal orientation of ulnar- and radial-sided fixation but rather that ulnar-sided fixation was simply in the plane of applied displacement forces rather than 90° out of plane. This too is a potential topic of further investigation.

The proposed standardization of the simulated fractures also might be called into question. Inasmuch as any cadaver model of fracture patterns can be standardized care was taken to meet this requirement. The specimens in Figures 1A and 2A appear to have had a sagittal osteotomy performed at slightly different locations. Although there is a slight rotational difference in these films this is still a true observation owing to the anatomic variation between specimens. The depicted specimens were not of the same matched pair. All fragments fixed with the fixed-angle volar plates were of sufficient size to accommodate 2 smooth pegs.

With subtle differences both the fragment-specific
and fixed-angle volar plate fixation systems performed satisfactorily, justifying claims of safe, early postoperative mobilization. A physiologic model of cyclic loading of an intra-articular distal radius fracture is relatively simple to use and lends itself to multiple applications.

The authors wish to thank Sione P. Fanua, MSc, for his assistance with specimen preparation and handling.

Received for publication June 11, 2005; accepted in revised form December 30, 2005.

No benefits in any form have been received from a commercial party related directly or indirectly to the subject of this article.

Supported by the Raymond M. Curtis Research Foundation; material assistance received from Hand Innovations, Miami, FL, and TriMed, Inc., Valencia, CA.

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense.

Corresponding author: Kenneth F. Taylor, MD, Orthopaedic Surgery Service, Tripler Army Medical Center, Honolulu, HI 96859-5000; e-mail: Kenneth.Taylor@amedd.army.mil.

Copyright © 2006 by the American Society for Surgery of the Hand

References


29. Dunning CE, Lindsay CS, Bicknell RT, Patterson SD, Johnson JA, King GJW. Supplemental pinning improves the stability of external fixation in distal radius fractures during