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Nonbridging External Fixation of Intra-Articular Distal Radius Fractures

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External fixation of distal radius fractures may be used in a bridging or nonbridging manner. Bridging external fixation of distal radius fractures typically relies on ligamentotaxis to obtain and maintain a reduction of the fracture fragments. Superior motion can be achieved as compared with plate fixation because of less interference with the soft tissue envelope [1]. Ligamentotaxis has several shortcomings, however, when applied to the treatment of displaced intra-articular fractures of the distal radius. First, because ligaments exhibit viscoelastic behavior [2], there is a gradual loss of the initial distraction force applied to the fracture site through stress relaxation [3]. The immediate improvement in radial height, inclination, and volar tilt are decreased significantly by the time of fixator removal [4]. Ligamentotaxis does not restore the normal volar tilt of the articular surface, nor does it reduce a depressed lunate fragment [5–8].

Bad outcomes associated with external fixation are often related to overdistraction. The degree and duration of distraction correlates with the amount of subsequent wrist stiffness [9]. Distraction, flexion, and locked ulnar deviation of the external fixator encourage pronation contractures. Distraction also increases the carpal canal pressure [10], which may predispose to acute carpal tunnel syndrome.

Bridging fixation does not lend itself to early wrist motion. Efforts to dynamically mobilize the wrist with joint spanning fixators have been largely unsuccessful. This is related to the difficulty in reproducing the complex kinematics of the carpus and the inability of the fixator to maintain ligamentotaxis throughout the entire arc of motion [11,12]. Good results have been achieved with nonbridging fixation of extra-articular distal radius fractures, which does allow early wrist motion. The final wrist range of motion and grip strengths are superior to those attained with bridging external fixators [13,14].

Reports of nonbridging external fixation (or radio–radial external fixation) for the treatment of intra-articular fractures are sparse and mostly restricted to the European literature [15–20]. Some investigators believe that intra-articular fractures are not suited for nonbridging external fixation and advise a transarticular application [21,22]. The use of currently available external fixators applied in a nonbridging manner may result in articular incongruity (Fig. 1A–G). This was evident in one reported clinical trial of 30 patients with Frykman type 7 and 8 fractures who were treated with the Delta frame nonbridging external fixator (Mathys Medical, Ltd.; Bettlach, Switzerland) [15]. Although favorable wrist motion was reported, the median intra-articular step was 2.8 mm (range, 0–9.1 mm), with a median intra-articular gap of 1.8 mm (range, 0–13.4 mm) [17].

Biomechanical considerations for external fixation

External fixation is considered flexible fixation [23]. The biomechanical requirements of external fixation for fractures of the distal radius are not known, because the magnitude and direction of

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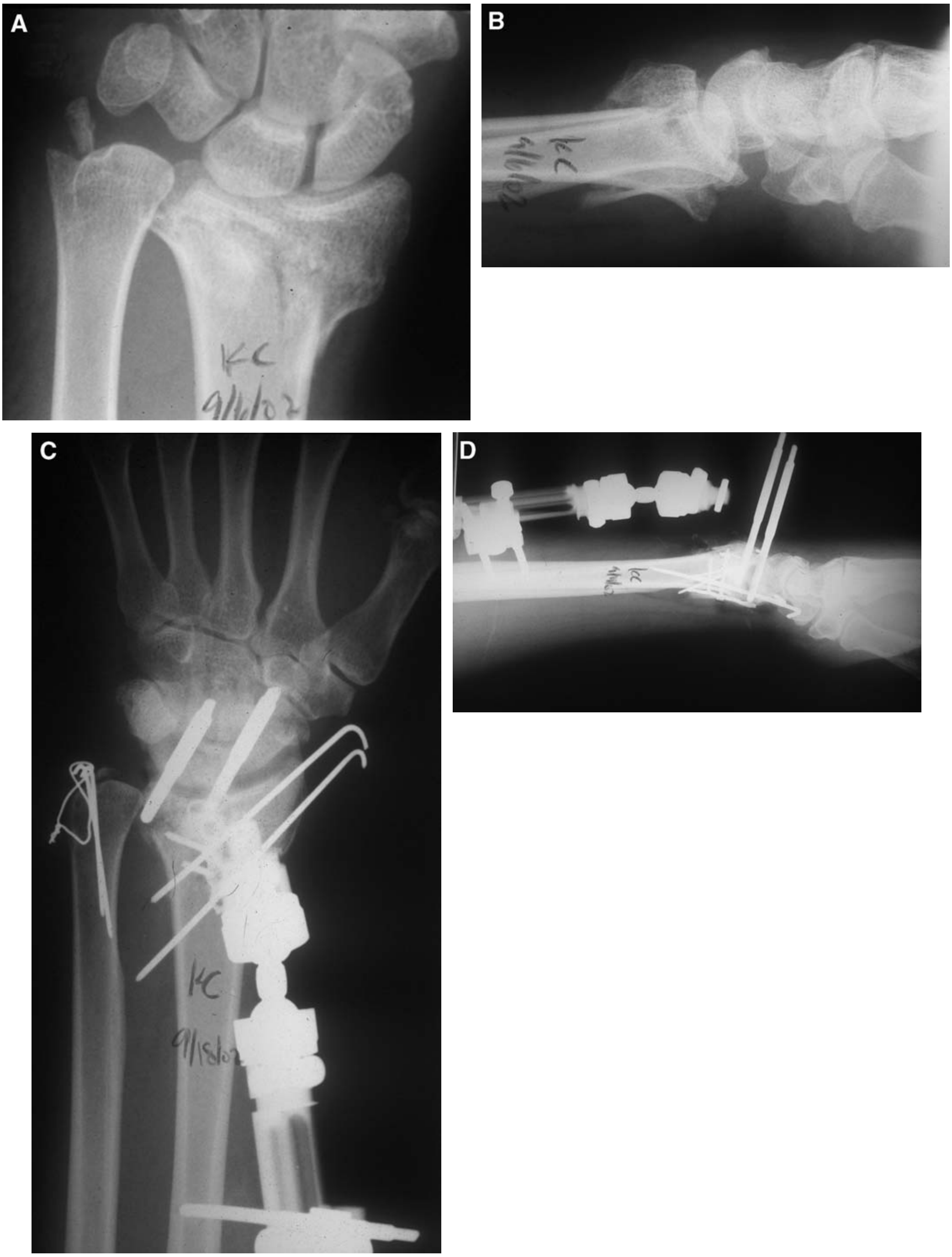

Fig. 1. A 61-year-old male: right distal radius fracture with an unstable distal radioulnar joint. (*A*) PA view demonstrating intra-articular extension plus an ulnar styloid fracture. (*B*) Lateral view demonstrating dorsal tilt and metaphyseal comminution. (*C*) Initial reduction with metaphyseal bone grafting and limited internal fixation of the volar-medial fragment. (*D*) Lateral view showing correction of dorsal tilt. (*E*) Clinical photo of nonbridging external fixator (EBI; Parsippany, NJ). (*F*) Note supplementary radial pin fixation. (*G*) Nine-month follow-up showing late collapse of radial styloid fragment.

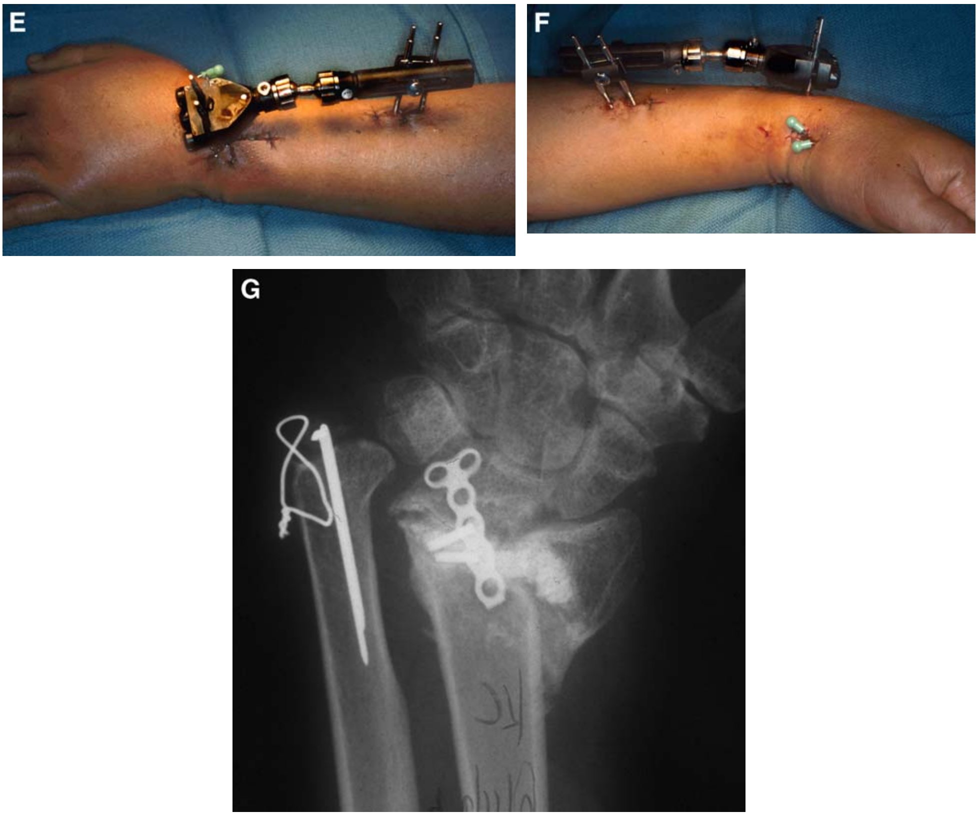

Fig. 1 (*continued*)

the physiologic loads on the distal radius are dynamic and unknown, even for the normal wrist [24]. Increasing the rigidity of the fixator does not appreciably increase the rigidity of fixation of the individual fracture fragments [25]. There are several ways, however, in which to augment the stability of the construct. After restoration of radial length and alignment by the external fixator, percutaneous pin fixation can lock in the radial styloid buttress and support the lunate fossa fragment [26]. A fifth radial styloid pin attached to the frame of a spanning AO (Synthes; Paoli, Pennsylvania) external fixator prevents a loss of radial length that can occur secondary to settling and leads to improved wrist range of motion as compared with a four-pin external fixator [27]. The addition of a dorsal pin attached to a sidebar easily corrects the dorsal tilt found in many distal radius fractures [28,29].

K-wire fixation enhances the stability of external fixation. The combination of an external fixator augmented with 0.62 K-wires approaches the strength of a 3.5-mm dorsal AO plate (Synthes) [30]. Supplemental K-wire fixation is more critical to the fracture fixation than the mechanical rigidity of the external fixator itself [25]. Stabilizing a fracture fragment with a nontransfixing K-wire that is attached to an outrigger is just as effective as a K-wire that transfixes the fracture fragments [31].

These observations were incorporated into the design of a biomechanical study to examine the feasibility of nonbridging external fixation of simulated three- and four-part intra-articular fractures [32]. The goal of the study was to determine whether fragment specific external fixation could provide sufficient stability to allow immediate wrist motion. A secondary goal was to define safe limits for the rehabilitation forces during passive assisted wrist motion and simulated gripping.

Materials and methods

The study was performed in three phases. In the first phase, the feasibility of this approach was tested in a three-part intra-articular fracture model using one or two external fixators applied in a nonbridging fashion. Safe anatomic intervals for pin placement of the proximal and distal radius were established by pre-dissection of the specimens. In one specimen the distal ulna was excised to remove any load sharing. In another specimen a section of bone was removed from the metaphyseal/diaphyseal region to simulate a segmental fracture with bone loss. The fracture fragments were held in a reduced position by two radial styloid pins and two dorsal pins (see section on pin configuration). The specimens underwent biomechanical testing with single and double nonbridging fixator configurations.

The second phase examined the maximum static force that could be withstood during simulated passive assisted wrist extension and simulated gripping without causing articular displacement in a four-part fracture model. All of the fractures were stabilized using a single custom nonbridging external fixator that incorporated a dorsal sidearm (the Fragment Specific Fixator, South Bay Hand Surgery Center, Torrance, California) (Fig. 2).

In the third phase the effects of cyclic loading were examined on a three-part intra-articular fracture model with dorsal comminution as described by Dodds et al [33]. All of the fractures were stabilized with the Fragment Specific Fixator.

Specimen preparation

Seventeen nonmatched fresh frozen above-elbow specimens were disarticulated at the elbow. All the soft tissues were removed except for the tendons of the primary wrist motors: the conjoined extensor carpi radialis longus and brevis (ECRL/B), the extensor carpi ulnaris (ECU), the flexor carpi ulnaris (FCU), and the flexor carpi radialis (FCR). A #0 braided polyester suture then was placed in a Bunnell fashion in each of the tendons. The volar wrist capsule and the volar ligaments, the pronator quadratus, and the interosseous membrane were left intact. In phase I and II, the dorsal capsule was excised to facilitate the creation of the intra-articular fractures and to

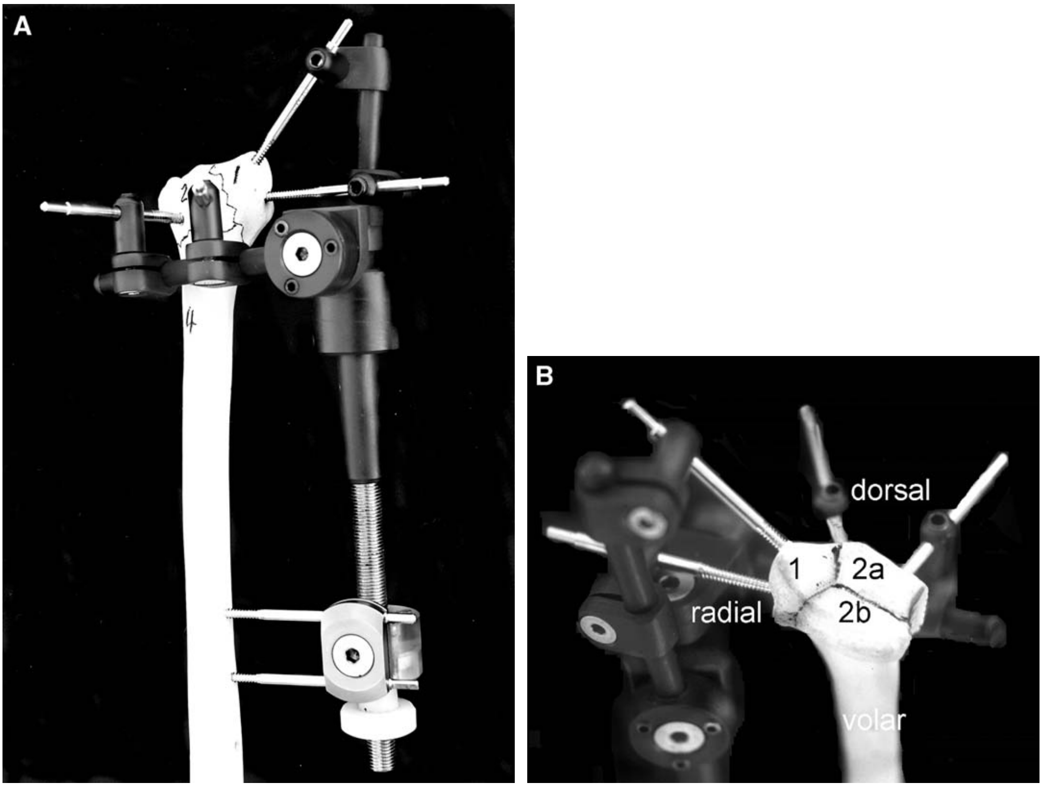

Fig. 2. (*A*,*B*) The fragment specific fixator demonstrating pin configuration in an intra-articular fracture.

assess the articular displacement after biomechanical testing. In phase III the dorsal radiocarpal ligament was elevated as described by Berger et al [34], and then repaired with the #0 braided nylon suture before testing. The below-elbow specimens were fixed in midrotation with three 0.062-mm crossed K-wires and potted vertically in cement. The specimens were refrigerated overnight to allow cement hardening and then were allowed to warm to room temperature for testing.

Osteotomy

In phase I a three-part fracture was outlined using drill holes that then were connected with an osteotome to create separate radial styloid and lunate fragments. In phase II the lunate fragment was osteotomized to create a dorsomedial and volar-medial fragment. The dorsal radioulnar ligament and the triangular fibrocartilage (TFC) insertion into the radius were cut arbitrarily in 4/8 specimens, to simulate a disrupted TFC. In phase III a three-part fracture was created, followed by excision of a 2-cm dorsal wedge to simulate metaphyseal comminution.

Pin configurations

The radial styloid fragment was stabilized by drilling a 3.0-mm threaded cortical pin from the tip of the radial styloid at an approximate 45° angle through the fracture site to engage the ulnar cortex of the proximal fragment. A second more proximal 3.0-mm pin was inserted horizontally into the medial fragment to provide subchondral support. Two 3.0-mm threaded pins were inserted dorsally into the lunate fragments. The available portals for distal pin placement corresponded to the standard intertendinous interval for wrist arthroscopy portal [35]. Radial sided pins could be inserted safely on either side of the first extensor compartment. Dorsal pins could be inserted between the extensor pollicis longus (3/-,4 portal), between the extensor digitorum and the extensor digiti minimi (4/-,5 portal) and between the extensor digiti minimi and the extensor carpi ulnaris (6R portal). The proximal pins could be inserted in the standard dorsoradial position or dorsally between the ECRB and extensor digitorum, which carries less risk for injury to the superficial radial nerve [36].

In phase I a modified Stableloc external fixator (Acumed, LLC; Hillsboro, Oregon) was applied dorsally and attached to the dorsal pins to maintain the height of the lunate fragment and to restore the normal volar tilt of the joint surface. In the two-fixator configuration, an AO fixator (Synthes) also was applied along the radial midaxial line and fastened to the radial styloid pins. Specimens #4 and #5 were tested only with the two-fixator configuration (Fig. 3).

In phase II and III the fragment specific fixator was applied along the radial midaxial line and clamped to the two radial styloid pins (Fig. 4*A–D*). The two dorsal 3.0-mm pins were attached to separate locking clamps on the dorsal sidearm. Reduction of the intra-articular gap between the radial styloid and lunate fragments was facilitated by sliding the dorsal pin clamps in a radial direction. Anatomic fixation of the joint surface was confirmed by direct visual inspection. The proximal fixator clamp then was attached to parallel 3.0-mm pins that were drilled into the proximal radial shaft.

Biomechanical testing

All of the specimens were mounted vertically with an 89-N preload (20 lb) [37] applied by way of gravity traction by hanging 5-lb metal plates from the wrist tendons. Active wrist motion was simulated by manually moving the wrist through a complete flexion and extension arc. Passive assisted wrist motion was simulated by applying an additional load to the carpus with a servohydraulic materials testing machine (Instron 1321 Biaxial Hydraulic System; Instron Corporation, Canton, Massachusetts). Gripping was simulated by direct axial loading of the lunate fossa [24].

Fig. 3. Two-fixator configuration stabilizing a three-part fracture.

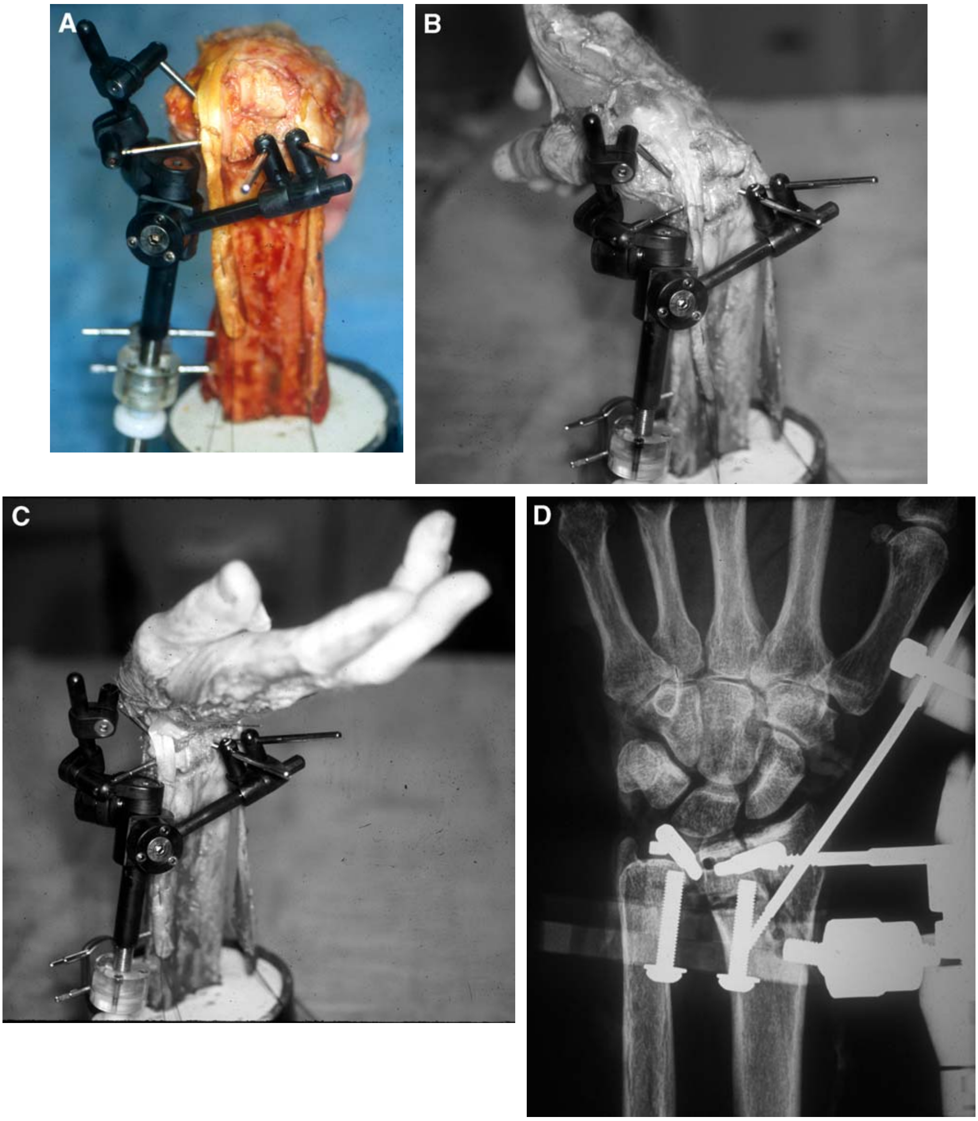

Fig. 4. (*A*) Fragment specific fixator in a three-part fracture with dorsal wedge osteotomy. (*B*) Demonstration of unrestricted wrist flexion. (*C*) Demonstration of unrestricted wrist extension. (*D*) AP radiograph showing pin fixation of a four-part fracture seen through the radiolucent dorsal sidearm of the custom fixator.

In phase I the specimens were tested twice, with the testing performed in two series. In each series, the testing commenced with the two-fixator configuration. The AO fixator was removed without disturbing the radial styloid pins and the testing was repeated. The constructs were initially loaded in extension, with the force applied to the palm of the hand at the level of the distal palmar crease. Testing in flexion was not possible because of the dorsal capsulotomy. The load was applied at a constant rate of 25 mm/min. Each specimen was loaded up to a maximum of 20 cm of displacement (from compression of the soft tissue) or to a maximum load of 100 N, whichever came first. The articular surface was inspected and any step-off between the scaphoid and lunate fossae was measured with calipers. In the second series, the preload was removed and the carpus was disarticulated. An axial load was applied directly to the lunate fossa at the same loading rate up to a maximum of 400 N. The articular surface was inspected again for any displacement.

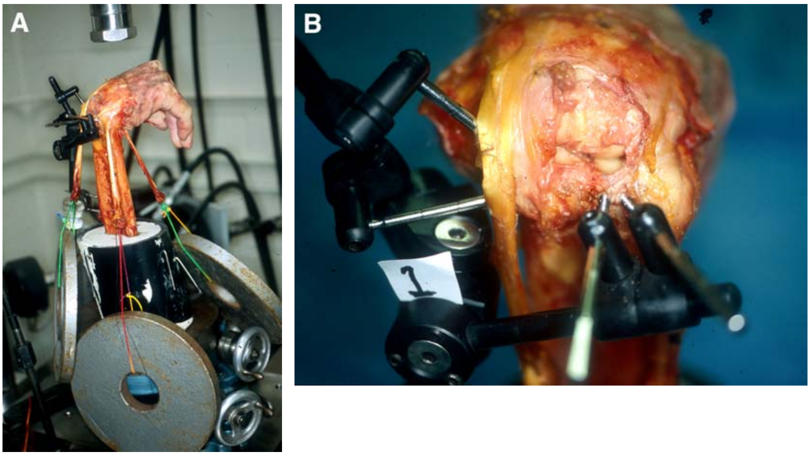

Fig. 5. (*A*) Biomechanical testing setup simulating passive assisted wrist flexion. Note the 20-lb preload. (*B*) Demonstration of a congruent articular surface after testing.

In phase II a four-part intra-articular fracture was created in eight arms and stabilized with the fragment specific fixator. In the first series an identical loading protocol was used, but the maximum load was increased to 400 N. In series two, the carpus was disarticulated and the preload was removed. The maximum axial load was increased to 600 N.

In phase III a three-part intra-articular fracture with a dorsal wedge osteotomy was performed in four arms and stabilized with the fragment specific fixator. Each specimen was tested twice. The wrist was taken through 100 cycles of flexion and extension with just the 89 N preload. The hanging weights were kept in place while additional load was applied directly to the carpus through the force plate of the Instron machine (Fig. 5*A*,*B*). The added load was applied for 100 cycles at a rate of one cycle every 2 seconds up to 20 mm of displacement. The constructs had disparate loading requirements due to the variable stiffness of the individual specimens. This difference resulted in loads of 45–55 N. The displacement was restricted to 20 mm, because higher amounts led to impingement of the back of the carpus on the dorsal sidearm of the fixator in some specimens. The combination of the 89 N physiologic load and the additional applied load thus ranged from 135–145 N.

Loading data

Data acquisition was made by the Instron Series IX software program (Instron Corporation, Canton, Massachusetts), which generated a force/displacement curve. Stiffness was defined as the slope of the straight-line region of the load-displacement curve. The secant of the slope, ie, the average line, was drawn through the slope, and the stiffness (Y/X) was calculated. Statistic analysis of the results was performed using a two-tailed student's *t*-test.

Results

Phase 1

In three constructs the mean stiffness of the one-fixator configuration in extension loading was 42.2 N/mm and was 75.8 N/mm with two fixators.

Table 1
Stiffness data for phase I

	Stiffness of extension (N/mm)		Stiffness of axial loading (N/mm)		
Specimen	1 fixator	2 fixators	1 fixator	2 fixators	Joint displacement
1	76.5	100.9	152.5	122.5	None
2	15.4	25.2	143.4	125.6	None
3	34.8	101.4	150.0	143.9	None
4	—	100.0	—	114.0	None
5	8.3	—	17.5	—	Yield point 40 N

Table 2
Stiffness data for Phase II

Specimen	Extension stiffness (N/mm)	Comment	Max. load (N)	Axial loading stiffness (N/mm)	Comment	TFC/DRUL	Max. load (N)
1	16.2	1 mm sagittal split at 330 N (sidearm impingement)	330	110.8		Cut	600
2	12.6		400	195.0		Intact	600
3	23.2		361	178.1		Intact	600
4	28.5		200	89.9	2-mm gap at 500 N	Cut	600
5	16.5		200	133.5		Intact	600
6	10.8		300	123.1	1-mm depression at 200 N	Cut	600
7	10.6		250	219.0		Intact	600
8	18.2		350	145.2		Cut	600
Mean	17.07			149.32			

The mean stiffness in axial loading was 148.6 N/mm with one fixator and was130.7 N/mm with two fixators (Table 1). These differences were not statistically significant. Despite the variation in stiffness, however, no joint displacement was observed. In the remaining two constructs, it was observed that removal of the distal ulna did not affect the stiffness significantly, although meaningful results cannot be drawn from only one specimen. Removal of a 4-cm segment of radius dramatically affected the stability of the construct. Fracture angulation could not be controlled, even with two fixators at low load levels (40 N); hence, the construct was not tested in axial loading.

Phase II

In the second study, the stiffness ranged from 10.6–28.5 N/mm in extension loading, with a mean of 17.1 N/mm, and ranged from 89.9–219.0 N/mm in axial loading, with a mean of 149.3 N/mm (Table 2). The mean stiffness of specimens in extension loading was 18.4 with an intact TFC and 15.7 N/mm with a cut TFC. This difference was not statistically significant. The mean stiffness of specimens in axial loading was 117.25 N/mm with an intact TFC and 181.4 N/mm with a cut TFC, which was statistically significant ($P = 0.039$).

During extension loading, there was gapping of the articular surface in 1/8 specimens caused by leverage on the dorsal sidearm by the carpus. In axial loading, there was a 2-mm gap in specimen #4 at 500 N, and a 1-mm lunate fossa depression in specimen #5 at 200 N.

Phase III

In the third study there was no observable articular displacement in any of the wrists after 200 cycles of wrist flexion and extension with loads of up to 145 N (Table 3).

Conclusions

There was a wide variation in the stiffness of the constructs during phases I, II, and III. Despite this variation, fragment specific external fixation was able to maintain articular congruity with forces that exceed physiologic loading. The stiffness of the construct stabilized with the fragment specific

Table 3
Data for phase 3

Specimen	Gender	Side	Physiologic load (N)	Applied load (N)	Combined load (N)	Articular displacement
1	M	R	89 N	55 N	144	None
2	F	L	89 N	40 N	129	None
3	F	L	89 N	45 N	134	None
4	F	R	89 N	55 N	144	None

Fig. 6. Comminuted intra-articular left distal radius fracture. (*A*) AP radiographic view of distal radius. (*B*) Sagittal CT view reveals multiple free articular fragments. C, capitate. (*C*) Coronal CT view highlighting the central comminution. U, ulna. (*D*) AP radiographic view demonstrating a congruent joint surface after limited internal fixation, bone grafting, and nonbridging external fixation. (*E*) Clinical photograph of nonbridging fixator at 6 weeks. (*F*) Lateral view of fixator.

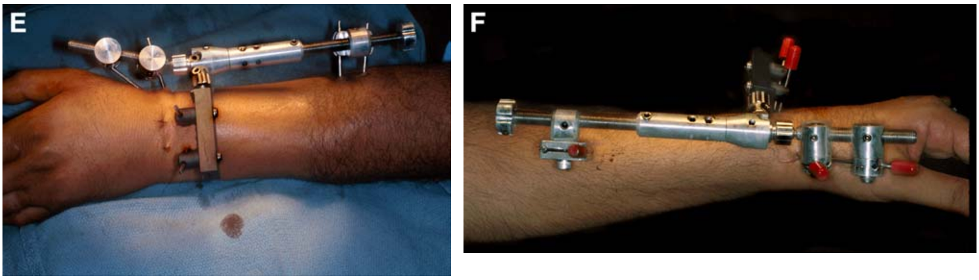

Fig. 6 (*continued*)

fixator averaged 149 N in axial loading with an intact TFC and 117 N with a cut TFC. These values compared favorably with the stiffness data of five commercially available distal radius plates, which ranged from 95.5–136.0 N [38].

In fragment specific external fixation, the fixator pins are used in place of K-wires. The fixator pins have dual roles. They provide interfragmentary fixation, but when attached to the fixator, they also act like blade plates to resist bending moments and buttress the fracture fragments. The immediate subchondral position of the pins supports the joint surface and is critical in maintaining articular congruity during fracture healing. Ligamentotaxis through joint bridging can be avoided to allow early wrist motion. Similar to a fixed-angle plate, the biomechanical rationale for the fragment specific fixator is to transfer load from the fixed support of the articular surface to the intact radial shaft, bypassing any metaphyseal comminution. Unlike a fixed-angle blade plate, the fixator pin angle is freely adjustable so that it can be adapted to the fracture site plane, which may diminish fracture malalignment.

Discussion

Early wrist motion following intra-articular fractures provides several possible benefits, including diminished stiffness, stimulation of cartilage repair [39], and decreased osteopenia of the distal fragments [17]. To accomplish this with nonbridging external fixation, the construct must be able to withstand the forces generated during active and passive wrist motion.

The physiologic forces across the wrist are not known and only can be estimated. Previous cadaver investigations have used a load of 88–135 N applied with weights or springs to the wrist tendons to simulate muscle forces [37,40–43]. Wolfe et al [31] and Osada et al [38] used a maximum load of 100 N to simulate the muscle forces exerted during active wrist joint motion as well as light activities of daily living (ADL) [31]. Other investigators have estimated that a 250-N load compares with the physiologic loads that occur during active digit flexion [38,44].

In phase I it was demonstrated that fragment specific nonbridging external fixation for intra-articular fractures was feasible. In phase II the use of the fragment specific external fixator controlled articular displacement under static forces that exceeded physiologic levels. In phase III there were no failures with loads of up to 145 N after 200 cycles of simulated active and passive assisted wrist motion. These observations therefore provide confidence for allowing active and passive wrist motion during the healing phase.

Whereas for every 10 N of grip force, 26 N is transmitted through the distal radius metaphysis, it has been recommended that the rehabilitation grip forces should be kept at less than 140 N with external fixation to prevent or minimize fixation failure [45]. The author therefore agrees that this is a safe limit as it pertains to nonbridging external fixation also. Although this study demonstrated the ability of the fragment specific fixator to withstand loads in excess of this, the author did observe 1 mm of articular depression in one specimen with a cut TFC at a 200-N axial load. The author recommends limiting aggressive passive assisted wrist exercise, gripping, and dynamic wrist splinting until there is some fracture site healing, because articular displacement of even 1–2 mm has been shown to lead to osteoarthritis [46–48].

Case report

A 49-year-old anesthesiologist presented with a 2-week-old distal radius fracture. A CT scan

Fig. 7. Follow-up at 15 months. (*A*) AP radiographic view showing maintenance of radial height and length but early radiocarpal narrowing. (*B*) Lateral view demonstrating neutral tilt. (*C*) Range of wrist flexion. (*D*) Wrist extension. (*E*) Pronation arc. (*F*) Supination arc.

revealed the true extent of the intra-articular comminution (Fig. 6A–C). He underwent an arthroscopic aided reduction of the fracture together with limited internal fixation of the volar-medial fragment and percutaneous bone grafting. Two radial and two dorsal pins were inserted and buttressed by the custom nonbridging fixator (Fig. 6D–F). He was allowed unrestricted wrist motion and he continued to work in his pain management practice. The pins and the fixator were removed at 6 weeks. Long-term follow-up demonstrated maintenance of the initial reduction. He had a functional arc of motion and minimal pain despite early radiocarpal arthrosis (Fig. 7A–F).

Caveats

Nonbridging external fixation of intra-articular distal radius fractures should be reserved for

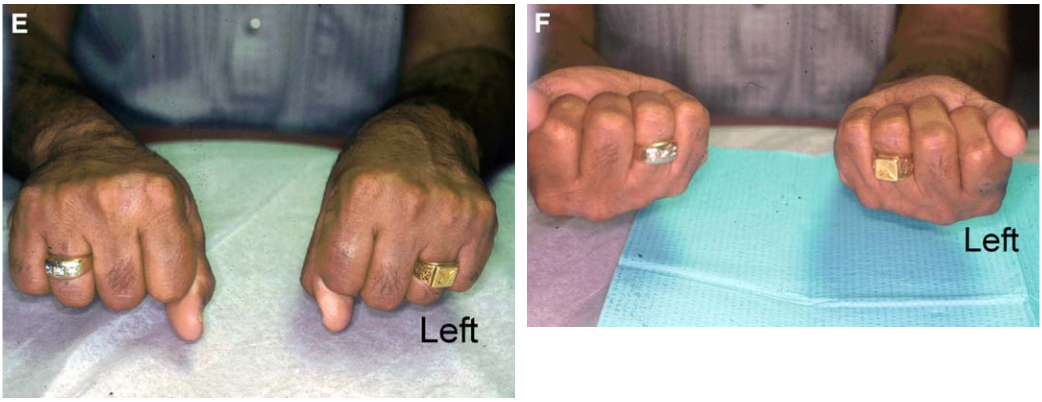

Fig. 7 (*continued*)

manually active patients with good bone quality without evidence of prior wrist arthritis. Any metaphyseal defects should be bone-grafted to minimize bending loads on the fixator. It is important to engage the palmar lip of the distal radius (where the bone density is highest) when inserting the dorsal pins, especially in osteopenic bone [22]. In four-part fractures, palmar translation and rotation of the volar-medial fragment should be treated with limited internal fixation [8,49,50].

Contraindications

Volar and dorsal marginal fractures (Barton's and reverse Barton's) are excluded and should be treated with internal fixation. Fractures with extensive metaphyseal/diaphyseal comminution and articular fractures in elderly inactive patients should be approached cautiously.

Summary

New solutions to difficult problems are always welcome, but nonbridging external fixation of intra-articular fractures is still in its infancy. Multicenter clinical trials are necessary to determine whether the superior results obtained with nonbridging fixation of extra-articular fractures can be duplicated. With further study and new fixator designs, it is anticipated that nonbridging external fixation of intra-articular distal radius fractures will become another viable treatment option.

References

[1] Slutsky DJ. A comparison of external vs internal fixation of distal radius fractures. Presented at the American Association for Hand Surgery Annual Meeting, Boca Raton, FL, January 10, 1997.

[2] Woo SL, Gomez MA, Akeson WH. The time- and history-dependent viscoelastic properties of the canine medical collateral ligament. J Biomech Eng 1981;103:293–8.

[3] Winemaker MJ, Chinchalkar S, Richards RS, Johnson JA, Chess DG, King GJ. Load relaxation and forces with activity in Hoffman external fixators: a clinical study in patients with Colles' fractures. J Hand Surg [Am] 1998;23:926–32.

[4] Sun JS, Chang CH, Wu CC, Hou SM, Hang YS. Extra-articular deformity in distal radial fractures treated by external fixation. Can J Surg 2001;44: 289–94.

[5] Axelrod TS, McMurtry RY. Open reduction and internal fixation of comminuted, intraarticular fractures of the distal radius. J Hand Surg [Am] 1990; 15:1–11.

[6] Bartosh RA, Saldana MJ. Intraarticular fractures of the distal radius: a cadaveric study to determine if ligamentotaxis restores radiopalmar tilt. J Hand Surg [Am] 1990;15:18–21.

[7] Sanders RA, Keppel FL, Waldrop JI. External fixation of distal radial fractures: results and complications. J Hand Surg [Am] 1991;16:385–91.

[8] Fernandez DL, Geissler WB. Treatment of displaced articular fractures of the radius. J Hand Surg [Am] 1991;16:375–84.

[9] Kaempffe FA, Wheeler DR, Peimer CA, Hvisdak KS, Ceravolo J, Senall J. Severe fractures of the distal radius: effect of amount and duration of external fixator distraction on outcome. J Hand Surg [Am] 1993;18:33–41.

[10] Baechler MF, Means KR Jr, Parks BG, Nguyen A, Segalman KA. Carpal canal pressure of the distracted wrist. J Hand Surg [Am] 2004;29:858–64.

[11] Sommerkamp TG, Seeman M, Silliman J, et al. Dynamic external fixation of unstable fractures of the distal part of the radius. A prospective, randomized comparison with static external fixation. J Bone Joint Surg [Am] 1994;76:1149–61.

[12] Kawaguchi S, Sawada K, Nabeta Y, Hayakawa M, Aoki M. Recurrent dorsal angulation of the distal radius fracture during dynamic external fixation. J Hand Surg [Am] 1998;23:920–5.

[13] McQueen MM. Redisplaced unstable fractures of the distal radius. A randomised, prospective study of bridging versus non-bridging external fixation. J Bone Joint Surg [Br] 1998;80:665–9.

[14] McQueen MM. Metaphyseal external fixation of the distal radius. Bull Hosp Joint Dis 1999;58:9–14.

[15] Krishnan J, Chipchase LS, Slavotinek J. Intraarticular fractures of the distal radius treated with metaphyseal external fixation. Early clinical results. J Hand Surg [Br] 1998;23:396–9.

[16] Krishnan J, Wigg AE, Walker RW, Slavotinek J. Intra-articular fractures of the distal radius: a prospective randomised controlled trial comparing static bridging and dynamic non-bridging external fixation. J Hand Surg [Br] 2003;28:417–21.

[17] Mehta JA, Slavotinek JP, Krishnan J. Local osteopenia associated with management of intra-articular distal radial fractures by insertion of external fixation pins in the distal fragment: prospective study. J Orthop Surg (Hong Kong) 2002;10:179–84.

[18] Gradl G, Gierer P, Ewert A, Beck M, Mittlmeier T. Radio-radial external fixation in the treatment of distal radius fractures allows for free wrist motion. Zentralbl Chir 2003;128:1014–9.

[19] Fischer T, Koch P, Saager C, Kohut GN. The radio-radial external fixator in the treatment of fractures of the distal radius. J Hand Surg [Br] 1999;24:604–9.

[20] Ziegler IP, Remiger A. Treatment of unstable distal radius fractures with a small AO-fixateur externe not bridging the joint. Unfallchirurg 1996;99: 836–40.

[21] Gausepohl T, Pennig D, Mader K. Principles of external fixation and supplementary techniques in distal radius fractures. Injury 2000;31(Suppl 1): 56–70.

[22] Gausepohl T, Worner S, Pennig D, Koebke J. Extra-articular external fixation in distal radius fractures pin placement in osteoporotic bone. Injury 2001; 32(Suppl 4):SD79–85.

[23] Juan JA, Prat J, Vera P, et al. Biomechanical consequences of callus development in Hoffmann, Wagner, Orthofix and Ilizarov external fixators. J Biomech 1992;25:995–1006.

[24] Gesensway D, Putnam MD, Mente PL, Lewis JL. Design and biomechanics of a plate for the distal radius. J Hand Surg [Am] 1995;20:1021–7.

[25] Wolfe SW, Austin G, Lorenze M, Swigart CR, Panjabi MM. A biomechanical comparison of different wrist external fixators with and without K-wire augmentation. J Hand Surg [Am] 1999;24:516–24.

[26] Seitz WH Jr, Froimson AI, Leb R, Shapiro JD. Augmented external fixation of unstable distal radius fractures. J Hand Surg [Am] 1991;16:1010–6.

[27] Werber KD, Raeder F, Brauer RB, Weiss S. External fixation of distal radial fractures: four compared with five pins: a randomized prospective study. J Bone Joint Surg [Am] 2003;85-A:660–6.

[28] Markiewitz AD, Gellman H. Five-pin external fixation and early range of motion for distal radius fractures. Orthop Clin N Am 2001;32:329–35 [ix].

[29] Braun RM, Gellman H. Dorsal pin placement and external fixation for correction of dorsal tilt in fractures of the distal radius. J Hand Surg [Am] 1994;19: 653–5.

[30] Dunning CE, Lindsay CS, Bicknell RT, Patterson SD, Johnson JA, King GJ. Supplemental pinning improves the stability of external fixation in distal radius fractures during simulated finger and forearm motion. J Hand Surg [Am] 1999;24:992–1000.

[31] Wolfe SW, Swigart CR, Grauer J, Slade JF III, Panjabi MM. Augmented external fixation of distal radius fractures: a biomechanical analysis. J Hand Surg [Am] 1998;23:127–34.

[32] Slutsky DJDQ. Fragment specific external fixation of distal radius fractures. Presented at the American Society for Surgery of the Hand 58th Annual Meeting. Chicago, IL, September 20, 2003.

[33] Dodds SD, Cornelissen S, Jossan S, Wolfe SW. A biomechanical comparison of fragment-specific fixation and augmented external fixation for intra-articular distal radius fractures. J Hand Surg [Am] 2002;27:953–64.

[34] Berger RA, Bishop AT, Bettinger PC. New dorsal capsulotomy for the surgical exposure of the wrist. Ann Plast Surg 1995;35:54–9.

[35] Abrams RA, Petersen M, Botte MJ. Arthroscopic portals of the wrist: an anatomic study. J Hand Surg [Am] 1994;19:940–4.

[36] Emami A, Mjoberg B. A safer pin position for external fixation of distal radial fractures. Injury 2000;31: 749–50.

[37] Short WH, Palmer AK, Werner FW, Murphy DJ. A biomechanical study of distal radial fractures. J Hand Surg [Am] 1987;12:529–34.

[38] Osada D, Viegas SF, Shah MA, Morris RP, Patterson RM. Comparison of different distal radius dorsal and volar fracture fixation plates: a biomechanical study. J Hand Surg [Am] 2003;28: 94–104.

[39] Salter RB, Simmonds DF, Malcolm BW, Rumble EJ, MacMichael D, Clements ND. The biological effect of continuous passive motion on the healing of full-thickness defects in articular cartilage. An experimental investigation in the rabbit. J Bone Joint Surg [Am] 1980;62:1232–51.

[40] Ruby LK, Cooney WP III, An KN, Linscheid RL, Chao EY. Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. J Hand Surg [Am] 1988;13:1–10.

[41] Palmer AK, Werner FW. Biomechanics of the distal radioulnar joint. Clin Orthop 1984;187:26–35.

[42] Trumble T, Glisson RR, Seaber AV, Urbaniak JR. Forearm force transmission after surgical treatment of distal radioulnar joint disorders. J Hand Surg [Am] 1987;12:196–202.

[43] Hara T, Horii E, An KN, Cooney WP, Linscheid RL, Chao EY. Force distribution across wrist joint: application of pressure-sensitive conductive rubber. J Hand Surg [Am] 1992;17:339–47.

[44] Yetkinler DN, Ladd AL, Poser RD, Constantz BR, Carter D. Biomechanical evaluation of fixation of intra-articular fractures of the distal part of the radius in cadavers: Kirschner wires compared with calcium-phosphate bone cement. J Bone Joint Surg [Am] 1999;81:391–9.

[45] Putnam MD, Meyer NJ, Nelson EW, Gesensway D, Lewis JL. Distal radial metaphyseal forces in an extrinsic grip model: implications for postfracture rehabilitation. J Hand Surg [Am] 2000;25:469–75.

[46] Fernandez JJ, Gruen GS, Herndon JH. Outcome of distal radius fractures using the short form 36 health survey. Clin Orthop 1997;341:36–41.

[47] Altissimi M, Mancini GB, Azzara A, Ciaffoloni E. Early and late displacement of fractures of the distal radius. The prediction of instability. Int Orthop 1994;18:61–5.

[48] Knirk JL, Jupiter JB. Intra-articular fractures of the distal end of the radius in young adults. J Bone Joint Surg [Am] 1986;68:647–59.

[49] Ruch DS, Yang C, Smith BP. Results of palmar plating of the lunate facet combined with external fixation for the treatment of high-energy compression fractures of the distal radius. J Orthop Trauma 2004;18:28–33.

[50] Harness NG, Jupiter JB, Orbay JL, Raskin KB, Fernandez DL. Loss of fixation of the volar lunate facet fragment in fractures of the distal part of the radius. J Bone Joint Surg [Am] 2004;86-A: 1900–8.