The Use of Circular Wire External Fixation in the Treatment of Salvage Ankle Arthrodesis

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The authors retrospectively reviewed their experience with circular wire external fixation in the treatment of salvage ankle arthrodesis during the past 9 years. The results of 43 cases in a difficult patient population are presented with an average follow-up of 27.0 months. Thirty-three patients (80.5%) went on to achieve a solid fusion or stable pseudarthrosis. A minimum of a 4-ring frame construct was applied for an average of 96.1 days. The major complication rate was 51.2%, including 3 below-knee amputations (7.3%), 7 unstable nonunions (17.1%), 7 cases of osteomyelitis and/or deep-space infection (16.3%), 3 malunions (7.3%), and 2 tibial stress fractures (4.7%). The incidence of complications occurred similarly in patients with Charcot arthropathy, failed total ankle arthroplasty, septic fusion, posttraumatic deformity, or avascular necrosis of the talus, whereas it was relatively higher in patients who were diabetics, smokers, or had an increased body mass index. In addition, the incidence of a nonunion tended to increase with longer follow-up, suggesting that early presumption of a solid union may be erroneous. Based on our defined criteria of a stable, well-aligned fusion without severe pain or activity restrictions, 28 patients (68.3%) had a good result. Circular wire external fixation can be a viable treatment for complex ankle salvage pathology; however, it is difficult to predict the prospects of success or failure. (The Journal of Foot & Ankle Surgery 44(1):22-31, 2005)

Key words: external fixation, Ilizarov, salvage ankle arthrodesis, Charcot

Salvage fusions of the ankle present a unique set of problems to the foot and ankle surgeon. In these cases, the surgeon must frequently deal with extensive scar tissue, bone and soft tissue loss, osteopenic bone, or anatomic changes that have occurred since the primary injury or surgery. Although there have been numerous advances in philosophy and technique during the past few years, many of the adaptations involved the use of internal or external fixation devices to stabilize the bony construct while awaiting consolidation (1). These devices have included screws, blade plates, retrograde intramedullary nails, and spanning monoplanar external fixators (2–10).

The use of internal fixation and some forms of external fixation, however, may not be possible or optimal when there has been extensive bone loss, local metabolic dissolution (Charcot arthropathy), active or latent infection, previous failure of fusion, osteopenia, and large soft-tissue defects. In some of these difficult cases, the complication rate is exceptionally high. Perlman and Thordarson (11) identified risk factors associated with ankle arthrodesis in a high-risk population. They equated open fractures; psychiatric disorders; diabetes mellitus; and tobacco, alcohol, and illegal drug use as major contributors to nonunion, and experienced a 28% nonunion rate (11). Frey et al (12) had similar findings, determining that predisposing factors to ankle nonunion include the type of fracture, avascular necrosis, infection, major medical problems, and open injury. They had an overall 56% complication rate and 55% nonunion rate with the use of an external fixator. However, only 11 of 78 patients in their trial had an external frame applied (12). Charcot arthropathy of the ankle is particularly challenging, because there is often resorption of the talar body, infection, and/or significant angular deformity with or without instability (13–15). In addition, there is a prolonged time to complete stable fusion, which may cause a loosening of

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fixation as the process evolves. Resultant deformity may further complicate the clinical scenario.

To provide salvage operations to this group of patients, alternative methods of fixation are necessary to provide stability for a prolonged period of time (15–21). Ring fixators are particularly suited for salvage fusions. Tensioned wires, bending stiffness, and torsional resistance, as well as stress shielding to underlying bone, allow for prolonged placement. These ring fixators use tensioned, small-diameter wires to achieve necessary stability and show optimal biomechanical characteristics for fracture healing (22, 23). This versatility is also useful in salvage ankle fusions, because modification of compressive or distraction forces can occur as fusion evolves (23, 24). Modulation of rotational, translational, neutralization, and angular parameters is also possible. In addition, adjunctive measures thought to increase fusion rates may be used to improve success rates, including internal bone stimulation, autologous growth factors, demineralized bone matrix, and auto or allograft supplementation (25–32).

The purpose of this investigation is to report the authors' experiences with external ring fixation in a clinical series of salvage ankle arthrodeses. It was anticipated that the complication rate would be rather high in this difficult group of patients. Second, we sought to determine if there was any improvement in the union rate with the use of external ring fixation for salvage fusion.

Materials and Methods

This outcome study was a retrospective review of clinical charts and radiographs from a series of consecutive patients who required a salvage arthrodesis of the ankle by using circular wire external fixators. For the purposes of this investigation, salvage was defined as any patient that had 1 or more of the following: 1) failed prior ankle arthrodesis; 2) a large bone loss or defect; 3) severe osteopenia, as determined by plain film radiography; 4) clinically significant instability usually from loss of bone mass; 5) active infection or history of osteomyelitis; and 6) soft-tissue defects. These criteria were evaluated and characterized by each operating surgeon. Patients were offered these salvage procedures as a last resort to achieve fusion, to relieve pain, to reduce deformity, to prevent recurrent ulceration, or to avoid proximal level amputation. In many cases, the index surgery was necessary to obtain a plantigrade foot.

Between 1995 and 2004, a total of 59 patients had revision ankle with or without hindfoot arthrodesis with various forms of external fixation performed at the authors' institution. All of the cases were performed by 2 of the authors (J.M.S. and S.M.R.) at Kaiser Permanente Medical Centers, with 47 patients at San Francisco and 12 patients at the Walnut Creek facility, respectively. These included monoplanar, biplanar, hybrid, and ring fixators. Out of this cohort, 42 patients had a circular fine-wire external fixator used in their respective surgery, and qualified for inclusion in this study.

The medical records of these patients were reviewed for the following factors: sex, height, weight, body mass index (BMI), social history, associated comorbidities, index injury or deformity, initial surgical procedures, the length of time that the frame remained in place, and postoperative complications. Success or failure of the arthrodesis, final position of the foot to the leg, and final ambulatory status were established as the endpoints of this study. The patients' final ambulatory status was characterized as either walking without assistance, or mobilizing with the use of a brace, crutches, cane, wheelchair, or other supportive device. The ultimate outcome was established at the time of latest clinical follow-up. An arbitrary deadline of July 2004 was selected for the endpoint.

Standard serial radiographs were taken preoperatively, and at regular postoperative intervals of 4 weeks until evidence of radiographic consolidation or nonunion was evident. Final healing was assessed by the level of radiographic bony callus formation at a minimum of 9 months postoperatively. For the purposes of this study, union was defined as unequivocal radiographic trabeculation across the arthrodesis site without clinical motion as confirmed by the operating surgeon. Nonunion was declared when there was still a visible cleft at the fusion mass and/or there was clinical motion at the fusion site. In some instances, fluoroscopic examination helped establish the presence of nonunion when radiographic consolidation was uncertain.

Success was defined as a stable union with a rigid, plantigrade ankle-foot complex, or a stable pain-free nonunion. A good result was considered when a stable fusion was achieved without major activity restrictions or debilitating pain. This included mild angular deformity ($\leq 5°$) in any plane, easily correctable with wedging, bracing, or shoe modification. A fair result was characterized as a stable fusion or hypertrophic nonunion with residual activity limitations. Severe complications, including unstable nonunion, angular deformity of $>5°$, or amputation, were deemed a poor result. Patient demographics and the presence or absence of radiographic consolidation were recorded and analyzed to determine if there was any correlation with final successful or failed outcome.

Major complications such as deep venous thrombosis (DVT), pulmonary embolism (PE), myocardial infarction (MI), deep-space infection, osteomyelitis, neurovascular injury, malunion, nonunion, tibial stress fractures, compartment syndrome, reflex sympathetic dystrophy, amputation, or death were recorded. Minor complications including pin-tract infection, pin-site irritation, stiffness, pain, impalement of musculotendinous structures, and broken hardware were

TABLE 1 Patient data

	Sex	Age (years)	BMI	Frame Duration (days)	Associated Diagnosis	Smoke	Index Injury	# Sx	Procedure	Bone Stimulator	Internal Fixation	Complications	Fusion Position	WB Status
1	M	56	24.4	91	None	No	Talar AVN	1	Pantalar fusion	No	Yes	Malunion	valgus	brace
2	M	47	32.5	92	DM1, kidney transplant	No	Charcot	2	Ankle fusion	No	No	Osteomyelitis	rectus	shoe
3	M	57	34.9	105	DM2	No	Charcot	2	Pantalar fusion	Yes	Yes		rectus	shoe
4	F	57	25.6	55	Spina bifida	No	Posttraumatic	3	Ankle fusion	Yes	No	Nonunion	—	wc
5	M	61	26.9	60	None	No	Failed total ankle	1	Ankle fusion	No	No		rectus	shoe
6	M	42	21.7	93	DM1	No	Posttraumatic	1	Ankle fusion	No	No		rectus	shoe
7	M	53	37.3	99	DM2, HTN, CAD	No	Posttraumatic	1	Ankle fusion	No	Yes	1) Osteomyelitis 2) Tibial stress fracture	rectus	shoe
8	M	42	28.2	85	Hepatitis B, HTN	No	Posttraumatic	1	Ankle fusion	No	No		rectus	shoe
9	F	47	42.9	120	DM1, HTN, chronic renal insufficiency	No	Septic fusion	1	Ankle fusion	No	Yes		rectus	shoe
10	F	45	31.6	77	DM1, HTN	No	Posttraumatic	1	Ankle fusion	Yes	Yes		≤5° varus	shoe
11	M	59	27	76	None	Yes	Septic fusion	1	Ankle fusion	No	No	Nonunion	—	wc
12	F	57	33.3	299	RA	No	Talar AVN	1	Tibiotalocalcaneal fusion	No	No	Nonunion	—	brace
13	F	43	39.7	104	DM1, kidney transplant	Yes	Charcot	2	Ankle fusion	Yes	Yes	1) Osteomyelitis 2) Tibial stress fracture 3) Malunion	varus (revised)	shoe
14	F	51	31.3	148	DM1, HTN	No	Septic fusion	2	Ankle fusion	Yes	Yes	1) Nonunion (stable) 2) Infected hardware	rectus	brace
15	M	28	27.1	128	None	Yes	Septic fusion	1	Ankle fusion	No	No		rectus	shoe
16	M	57	26.5	98	None	No	Failed total ankle	2	Ankle fusion	Yes	No	Nonunion → BKA	—	wc
17	M	65	30	60	DM2, HTN	Yes	Septic fusion	1	Ankle fusion	No	No	Unresolved infection → BKA	—	wc
18	M	65	23.7	87	None	No	Failed total ankle	1	Ankle fusion	Yes	No		rectus	shoe
19	F	55	32.1	90	DM2	No	Septic fusion	5	Ankle fusion	Yes	No		rectus	shoe
20	M	63	28.1	93	DM2	No	Charcot	2	Ankle fusion	Yes	No		rectus	shoe
21	M	26	23.7	48	DM1	No	Septic fusion	3	Ankle fusion	No	No		≤5° varus	shoe

22	F	57	24.8	103	None	No	Septic fusion	1	Ankle fusion	Yes	No		rectus	shoe
23	M	55	30.1	82	Charcot-Marie-Tooth	No	Posttraumatic	1	Ankle fusion	Yes	No		rectus	shoe
24	M	45	25.8	70	None	No	Septic fusion	1	Ankle fusion	No	No		rectus	shoe
25	M	59	28.2	119	None	Yes	Septic fusion	5	Ankle fusion	Yes	No	Nonunion	—	
26				124			Revision		Tibiocalcaneal fusion	Yes	No		rectus	shoe
27	M	60	27.3	106	DM1, HTN	No	Charcot	2	Pantalar fusion	Yes	Yes	Infected hardware	rectus	shoe
28	M	58	50.8	82	DM2, 3° syphilis	No	Charcot	2	Ankle fusion	No	No	Nonunion	valgus	wc
29	M	63	35.9	73	HTN	No	Septic fusion	4	Ankle fusion	Yes	No	Deep-space infection	rectus	shoe
30	M	38	27	93	Multiple sclerosis	No	Posttraumatic	4	Ankle fusion	No	Yes		≤5° valgus	shoe
31	F	37	22.2	82	None	No	Posttraumatic	2	Tibiocalcaneal fusion	Yes	No		rectus	shoe
32	F	50	43.1	119	DM2	Yes	Posttraumatic	4	Ankle fusion	No	Yes	Malunion	valgus (revised)	shoe
33				91			Revision		Tibiotalocalcaneal fusion	No	Yes		rectus	shoe
34	F	64	30.9	101	DM1, HTN, CHF	Yes	Charcot	2	Ankle fusion	Yes	No		rectus	shoe
35	M	59	32.6	84	HTN, CAD	No	Posttraumatic	2	Tibiotalocalcaneal fusion	No	Yes		rectus	shoe
36	M	29	19.4	103	None	Yes	Posttraumatic	3	Ankle fusion	No	Yes	Nonunion	—	wc
37	F	65	32.9	93	DM2	No	Charcot	2	Tibiotalocalcaneal fusion	Yes	Yes	Deep-space infection → BKA	—	wc
38	M	62	36.4	84	None	Yes	Septic fusion	4	Ankle fusion	Yes	No	Nonunion (stable)	rectus	brace
39	F	41	25.7	67	HIV+, Hepatitis C	No	Posttraumatic	4	Tibiocalcaneal fusion	Yes	Yes	Nonunion (stable)	rectus	brace
40	M	59	31.7	74	DM2, RA	No	Charcot	2	Ankle fusion	Yes	No	Nonunion (stable)	rectus	brace
41	M	61	28.5	93	None	Yes	Posttraumatic	1	Ankle fusion	No	Yes		rectus	shoe
42	M	49	25.8	92	DM2, HTN	No	Charcot	3	Ankle fusion	No	Yes		rectus	shoe
43	F	66	46.9	91	DM2, HTN	No	Charcot	2	Ankle fusion	Yes	Yes		rectus	shoe

Abbreviations: BKA, below-knee amputation; CAD, coronary artery disease; CHF, congestive heart failure; DM, diabetes mellitus type 1 or 2; HTN, hypertension; PVD, peripheral vascular disease; RA, rheumatoid arthritis; Sx, surgery; WB, weightbearing; WC, wheelchair.

excerpted from the medical record as determined by the operating surgeon.

Surgical Technique

A general surgical scheme was followed for all patients. The patient was placed supine on the operating table after induction of spinal or general anesthesia. The limb was always prepped and draped above the knee to facilitate alignment of the extremity. Tourniquet control was used on a case-by-case basis. Surgical exposure was obtained, usually through a midline incision over 1 or both malleoli. Removal of any preexisting fixation and debridement to viable bleeding bone was performed. Surface preparation of all exposed bone was accomplished in a variety of techniques including curettage, planing, resection, scalloping, and fenestration, dependent on intraoperaive inspection and presentation. Malleolar osteotomies were performed if access to the talus was needed for preparation or to achieve coaxial alignment of the foot to the leg.

Gross alignment of the extremity was achieved. The foot was centralized to the long axis of the leg and positioned posteriorly until just before bony apposition would be compromised. The lateral talar process, if present, was used as a reference point during this posterior translation. It should pass through a longitudinal bisection of the tibia on direct lateral projection in order to reduce the lever arm bending moment across the fusion site. In most cases, large-caliber Steinman pins were used to temporarily secure the final position of fusion. Once the final position of the foot to the leg was attained, additional bony and/or soft-tissue procedures in the hind, mid, or forefoot were performed to render a plantigrade foot.

In all cases, the tibiotalar, tibiocalcaneal, or tibiotalocalcaneal arthrodesis was attempted to be aligned in neutral in the sagittal and coronal planes and in 15° of external rotation (33). The ring fixator was then applied to the extremity under fluoroscopic control, securing the entire reconstructive mass with at least 2 rings above and 2 rings below the ankle. Additional rings proximal and distal to the fusion site were used as needed, depending on the stability of the construct. All of the external fixators were assembled for a static configuration, because there was no residual deformity correction. In addition, compression was usually determined to be detrimental given the large bony defects. The salvage procedures were intended to be single stage corrections; however, frame alterations and modifications were performed postoperatively if positional changes were necessary (Table 1). The interstices and defects were packed tightly with a combination of harvested autologous bone graft from either the iliac crest bone or distal tibial metaphysis, demineralized bone matrix, crushed cancellous allograft, and/or autologous platelet-derived growth factors. There was no standard recipe regarding the use of any or all of these materials. Implantable bone stimulators were used on a case-by-case basis (Table 1).

Unless undergoing a septic fusion, all patients received appropriate perioperative antibiotic prophylaxis. Septic fusions were treated with parenteral antibiotics targeted to a specific culture susceptible organism until the underlying infection was controlled. In cases of osteomyelitis of the distal tibia and/or talus, control of the infection with debridement(s) and antibiotic impregnated beads preceded the index procedure.

All patients were admitted for observation, pain control, and parenteral antibiotics if necessary. A customary postoperative pin and frame care protocol was implemented and consisted of daily cleansing by using either isopropyl alcohol, hydrogen peroxide, or soap and water. Strict lower-extremity elevation and nonweightbearing was prescribed. Frame removal was performed either in the office or under regional or general anesthetic when radiographic union, nonunion, or pseudarthrosis was established. After frame removal, a short-leg nonweightbearing cast was applied for an additional period of time ranging from 2 to 6 weeks. Patients were then progressed to a fracture walker and encouraged to gradually increase their weightbearing to tolerance.

Results

The clinical results and individual patient characteristics are summarized in Table 1. There were 28 men and 14 women. One death occurred in a male patient from complications associated with viral pneumonitis 27 days into the postoperative course. There was no evidence of PE, MI, or stroke found at autopsy. The patient was significantly immunocompromised with multiple medical conditions, including type 1 diabetes mellitus and end-stage renal disease. Because it is not known if the surgery further contributed to the patient's cardiopulmonary compromise secondary to decreased mobility, the patient was eliminated from our outcome calculations. This resulted in 41 patients who underwent a total of 43 salvage hindfoot/ankle fusions with a circular wire fixator. The average age of the patients at surgery was 52.5 years (range, 26–66 years). Most patients were obese with an average BMI of 30.3 kg/m^2 (range, 19.4–50.8 kg/m^2), and weight of 210 pounds (range, 110–375 pounds). Nine patients had type 1 and 11 had type 2 diabetes mellitus with an average HgA1C of 10.0 and 7.63, respectively. Two patients were diagnosed with rheumatoid arthritis. Ten patients were active smokers at the time of surgery.

Our salvage patients were composed of 13 posttraumatic ankle fusions, 2 cases of talar avascular necrosis (AVN), 11 Charcot deformities, 12 septic ankles, and 3 total ankle

arthroplasty revisions. The patients had undergone an average of 2.1 procedures prior to salvage arthrodesis (range, 1–5). Circular wire frames were generally fashioned with 2 rings above and 2 rings below the ankle when possible and secured with a combination of half-pins and tensioned olive or smooth wires. Time to frame removal averaged 96.1 days (range, 48–299 days). Postoperative follow-up at the authors' institution averaged 27.0 months (range, 6.1–59.1 months), including clinical assessment visits and radiographic evaluation.

Seventeen patients (41.5%) developed 22 major complications in our series, resulting in a major complication rate of 51.2% in 43 cases. Seven patients (17.1%) had unstable nonunions and 4 patients (9.8%) had a stable pseudarthrosis after the initial salvage surgery. One of the patients with an unstable nonunion was revised and subsequently fused, whereas another ultimately underwent a below-knee amputation, reducing the number of remaining unstable nonunions to 5 (12.2%). Osteomyelitis and/or deep-space infection occurred in 7 cases (16.3%) and subsequently treated with serial debridements and parenteral antibiotics. Three patients (7.3%) developed a malunion of $>5°$ angulation. Two of these patients required a revision supramalleolar osteotomy by using a circular wire frame and traditional internal fixation techniques, respectively. Tibial stress fracture occurred after frame removal in 2 cases (4.7%). None of our cases required a free flap or skin graft for coverage during the salvage procedure. There were 3 below-knee amputations (7.3%) that occurred, 2 secondary to intractable infection and 1 because of chronic pain after a nonunion. Of the 2 infected amputees, 1 patient with a history of Charcot arthropathy developed a deep-space infection postoperatively that did not respond to treatment, whereas the other never recovered from his primary septic ankle joint. The final amputation occurred in a patient after salvage fusion of a failed total ankle arthroplasty who developed a painful, unstable nonunion. There were no incidences of neurovascular insult, PE, DVT, MI, or compartment syndrome.

The major complication rate was relatively higher for smokers and patients with an increased BMI or diagnosis of diabetes mellitus (Table 2). Thirty-three patients ultimately went on to achieve complete fusion or stable nonunion (80.5%). Final position was either rectus or $\leq 5°$ angulation in 28 of 29 patients who achieved fusion (96.6%). At final follow-up, 28 patients (68.3%) were ambulatory with a regular or custom shoe and had a good result based on our defined criteria. Five patients (12.2%) required supportive bracing (4 stable pseudarthroses and 1 malunion) and had a fair result. Eight patients (19.5%) had a poor outcome and were confined to a wheelchair or used a prosthesis (5 unstable nonunions and 3 below-knee amputations).

Table 2 Summary of patient cohort with complication and unstable nonunion rates

	# of Patients	# of Major Complications	# of Unstable Nonunions
Diabetes Mellitus	20	13	1
BMI ≥30	20	14	2
Smoker	10	8	3
Supplemental internal fixation	18	12	1
No internal fixation used	23	10	6
Bone stimulator implanted	22	11	3
AVN of talus	2	2	1
Septic fusion	12	5	2
Posttraumatic	13	5	2
Failed total ankle arthroplasty	3	2	1
Charcot	11	8	1
TOTAL	41	22	7

Discussion

A wide variety of surgical options and approaches exist to tackle the difficult problem of a salvage ankle arthrodesis. Because the majority of these patients suffer from a substantial amount of segmental bone loss, osteopenia, or infection, internal fixation and some types of external fixation can be inadequate for stabilization of these pathologies and may potentiate nonunion. Active infection is an absolute contraindication to any implantable hardware, whereas osteoporotic bone or segmental defects may not lend themselves to internal fixation (16, 34, 35). Although external fixation can obviate some of these problems, monoplanar, biplanar, or hybrid frames do not provide the 360° rotational stability and rigidity of a circular wire frame. Additionally, circumferential dampening and distribution of the forces acting on the fusion mass are not possible with eccentrically placed fixators (36). There is also a lack of sagittal plane stability in nonring fixators, which are prone to increased bending moment forces in the anteroposterior plane (37–39). Circular wire frames can avoid these shortcomings by spanning the fusion interface and resisting destructive forces, regardless of the plane in which they occur. Increased stability is gained from spanning the arthrodesis site with multiple levels of fixation, allowing for the rigid, sturdy support required for a revision arthrodesis. The minimum 4-ring construct used for all of our procedures is one of the strongest configurations available and is optimally suited for the management of complex nonunions (40, 41).

There are occasions where internal fixation is appropriate when used in conjunction with an external frame because it can continue to provide resistance to shear force once the frame is removed. Disadvantages of internal fixation include possible stress risers created from the indwelling

fixation, and other problems associated with the retained hardware itself, including prominence and bacterial colonization. Additionally, depending on the amount of internal fixation initially applied, necessitation for removal of this hardware may leave a large defect requiring bone graft for stabilization. In our study, it is interesting to note that the rate of unstable nonunion was relatively lower in patients who had supplementary internal fixation used with their ring fixators (5.6% vs 26.1%). However, this may be misleading, in that many of the patients that received internal fixation could be presumed to have had either more bone mass or greater bone density. Similarly, internal fixation may have been inappropriate in patients with soft-bone or large bony defects.

The fusion rate in salvage ankle arthrodesis ranges between 77% and 100% in the modern literature (2, 42–46). Many patients in the external fixation studies, however, experienced an increased number of complications and prolonged time to fusion as compared to standard internal fixation alone. This data can be further stratified into types of salvage performed and their respective union rates: failed total ankle arthroplasty (78%–89%), septic fusion (84.2%–86.6%), and Charcot arthrodesis (90.1%–100%) (10, 13, 14, 17, 34, 47–49). Our results were similar in these patient populations, with fusions or stable nonunions in 66.6%, 83.3%, and 90.9%, respectively. Our overall union rate of 70.7% and success rate of 80.5% in a highly complicated patient population compares favorably with these studies. It is not known why the fusion rate differs among these patient pools, because the contributing variables may be multifactorial. We can assume that the consolidation rates are lower in patients with substantial amounts of bone loss, instability, or infection in failed total ankle arthroplasty or septic fusion. Yet, we were surprised that our fusion rate was higher in Charcot arthropathy. However, we were careful to perform these procedures when the acute Charcot process had quieted down and there was no clinical evidence of an active process. In our series, both patients with talar AVN developed a major complication, with a malunion and unstable nonunion, respectively. The impaired vascularity of the fusion mass secondary to aseptic necrosis of the talus may play a large role in these failures.

Because nonunion cannot be eliminated completely, the rate can be greatly reduced with adherence to several general principles. Our postoperative protocol of strict nonweight bearing with static frame placement was standard throughout the patient population. Numerous comorbidities, high BMI, large segmental bone defects, and osteopenic bone were all considered complicating factors. It is well established that smoking has deleterious effects on bone healing, evidenced by the substantially higher complication rate (80.0%) in our study (50, 51). We wanted to minimize the risk of failure that may be potentiated by weightbearing. In our opinion, weightbearing before bony consolidation is not recommended. The external frame serves to protect the arthrodesis site and should not encourage the patient to ambulate. Although weightbearing may be appropriate in those patients in whom the fixator is contained in the hard cortical bone of a healthy tibial shaft, the fixators applied to the patients in our study were more distal and crossed the ankle arthrodesis site. In addition, the quality and quantity of bone in this cohort could not be characterized as normal. The patients underwent an average of 2.1 procedures before salvage arthrodesis and consequently suffered from disuse osteopenia and additional bone and/or soft tissue loss. Displacement of the arthrodesis, stress fracture, or hardware failure are not acceptable consequences. Yet, we appreciate that the nonweightbearing regimen may place additional burdens on each patient. In addition to the marked change in lifestyle and activities of daily living, there may have been some indeterminate effect on the cardiopulmonary reserve of these patients. However, there were no incidences of MI in our series. Preoperative assessment of cardiac status was obtained in the higher risk group consisting of obese patients, those over age 55, or with a history of unstable hypertension, diabetes, or coronary artery disease (52–54).

A versatile approach may help to promote arthrodesis. In our study, adjunct measures taken in an attempt to accelerate fusion included autogenous tricortical iliac crest bone grafting, demineralized bone matrix, platelet-derived growth factors, and implantable bone stimulation. It is not known, however, if a single or combination of these measures had any effect on arthrodesis. These cases were performed during an extended period of time, when new technologies became readily available. Additionally, there was some case-dependent variability in the operating surgeon's mentality on the use of these products. These surgeries are intended to be limb-salvage procedures. Failure may not lend itself to additional revisions and may predispose the patient to amputation.

Although we defined an unstable non-union as a poor result or failure, some patients have a stable, functional, painless nonunion. They are ambulatory, whereas before surgery, they were not able to bear weight on their symptomatic extremity. Many judge success or failure of their procedure based on fusion rate. A solid, well-aligned arthrodesis should be the goal from the outset of any fusion procedure. However, we qualified a pseudarthrosis as a fair result if it was stable and the patient was able to tolerate the use of a brace without significant pain or recurrence of a condition or deformity.

Consideration must also be given to overall lower-extremity alignment. When placing the fusion mass in the final, optimal position, it is imperative that it not deviate from alignment with the mechanical axis of the tibia. The importance of coaxial alignment cannot be understated, because any deflections from neutral can place significant stresses through the arthrodesis site that may impede fusion

or alter gait efficiency. Two of our patients required realignment osteotomies through the malunited arthrodesis. These revisions helped to prevent ulceration and to reduce stress on adjacent joints by attaining a plantigrade foot. This concept was also applied to the intraoperative correction of residual pedal deformities that were present before, or unmasked by, the salvage ankle arthrodesis. These additional procedures did not appear to affect our fusion rate, because they were performed distal to the arthrodesis site and were managed with the same nonweightbearing protocol.

Minor complications were expected incidents, necessitating only conservative treatment or low-complexity surgical intervention. Moreover, they were so common in our series that we did not record the number of simple pin-tract infections treated with oral antibiotics or broken tensioned wires that were either removed or replaced. Conversely, major complications that could cause loss of limb or life, or otherwise seriously compromise the final result, were detailed to determine our true complication rate (55).

Salvage patients require longer surgical and rehabilitation time, a prolonged postoperative course, longer hospital stay, longer duration of antibiotic treatment, and limitations on weightbearing. In addition, the potential for infection and other major complications are significantly greater than with primary below-knee amputation alone (56). Patients with diabetes may be prone to contralateral Charcot changes with subsequent foot and/or ankle breakdown secondary to increased load on the nonoperative extremity (57, 58). However, in many cases, patients are not amenable to voluntary amputation, which is an expensive and morbid option (59). They may be willing to undergo a limb-salvage procedure, despite a relatively high failure rate and prolonged rehabilitation. In addition to the psychologic impact of amputation, there is increased cardiopulmonary compromise (56). Patients with below-knee amputations experience a higher mean oxygen consumption, decreased ambulatory velocity, and an overall increased energy expenditure (60–62). Nevertheless, amputation rates in salvage ankle fusions using external fixation are fairly low, ranging between 0% and 14%, and are likely the result of severe pain or untreatable infection (3, 34, 42, 43, 45, 46). Our 7.3% amputation rate was a similar finding.

In the lower extremity, the hindfoot-ankle complex is essential to bipedal gait. Surgical goals are to create a stable, plantigrade foot, with the ability to ambulate or function without pain. Massive trauma, severe deformity, or irreversible neurovascular damage are generally considered primary indications for an amputation, which may be warranted in lieu of heroic efforts at limb salvage (17, 56, 63–67). It is crucial to identify and satisfy both the surgeon's and the patient's expectations. Patients often seek second opinions for limb salvage and are less likely to be agreeable to an amputation. They should be counseled and informed that salvage may impose not only occupational and lifestyle adjustments on them, but quite possibly significant durations away from accustomed daily activities. Tolerance to such a prolonged course of events should be assessed preoperatively.

The surgeon must take great care in choosing the proper candidate for frame application. A patient's medical, social, and psychologic status should be contemplated before surgical commitment. Support structure, potential lost wages, and time off necessary for recuperation should be considered as well. Ultimately, the patient's desired lifestyle and ability to effectively rehabilitate both physically and mentally must be considered. The increased number of wires used in a circular frame can lead to pin-associated complications including pin-tract infections, loosening, and soft-tissue injury such as neurovascular or musculotendinous impalement (68, 69). The frames themselves are expensive, cumbersome, and aesthetically displeasing.

Salvage ankle procedures are technically demanding with an appreciably steep learning curve. It is not the purpose of this study to tout the broad use and appeal of ring fixators for salvage arthrodesis, because they are by no means a guarantee of fusion. In fact, it is possible that an alternative procedure or choice of fixation will have produced a similar result in our patient population. However, in some of these cases, external fixation seemed to provide the best choice, given the large bone loss, time to fusion, and soft bone in this patient population. Perhaps it is not the technique used but the extent of the primary injury and the patient's comorbidities that are primarily responsible in the determination of fusion rate (34). Whether arthrodesis is successful or not, custom shoeing and/or bracing may be necessary to control postoperative alignment, motion, and dispersal of forces.

There are several limitations to our study. Ideally, the follow-up time would be longer, because the effects of ankle arthrodesis on adjacent joints are well known (33, 61, 70, 71). Our average follow-up time of 27.0 months was adequate for an initial assessment of procedural efficacy, but intermediate and long-term outcomes may drastically differ. In fact, a number of the patients with nonunion manifested late, after the initial assessment of the overall result was that of a solid union. This suggests that apparent consolidation of the fusion mass can be misleading until the patient assumes full loading capabilities of the involved extremity.

Limb-length discrepancy was not evaluated; however, any significant postoperative shortening was corrected with heel lifts or other shoe modifications. Consideration of the preoperative severity of several factors, including deformity, was unable to be assessed. Moreover, the data collected was only from the authors' perspective and did not consider the patient's perception of their clinical outcome. Further functional analysis is necessary to determine if patients are truly better off with circular frame salvage

arthrodesis compared to amputation or just living with their condition.

This study also suffered from drawbacks inherent to a retrospective review. An attempt was made to glean as much information as possible from the medical records; however, as is common with large paper-based facilities, there were certain records unobtainable for complete review. The sample size was insufficient and the parameters were too multifaceted to produce statistically significant results. Yet, careful conceptual benefits can be realized from critical and objective analysis of this complex patient population.

Conclusion

Salvage ankle arthrodesis with external fixation can be a difficult undertaking and should be performed by an experienced surgeon after appropriate preoperative planning. Each case is unique and fraught with its own difficulties and inherent complications. Multiple variables preclude accurate prediction of the likelihood of success or failure.

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