Abstract
Fractures of irradiated bones present special challenges to healing. Nonunions are very common and are challenging surgical problems. We report three radiated nonunions of the clavicle successfully treated with modifications of standard internal fixation techniques.

Radiation therapy is commonly used in the treatment of numerous malignant tumors. Therapeutic doses of radiation can lead to weakened, devascularized, and fractured bones. Doses of radiation less than 3,000 rads do not prevent healing of pathologic fractures of long bones, especially when combined with open reduction and internal fixation (ORIF). However, pathologic fractures subsequent to radiation dosages exceeding 3,000 rads without the benefit of ORIF do not unite. The clavicle is commonly included in the radiation treatment field for cancers of the neck, breast, and forequarter regional lymph nodes. Furthermore, the clavicle is one of the most frequently fractured bones, although nonunion is uncommon. Clavicle fractures occurring in high-dose radiation fields will not unite. A review of the literature did not reveal any contributions addressing treatment of radiated nonunions of the clavicle. We present successful surgical treatment of three patients who underwent high-dose radiation treatment for cancer and subsequently suffered pathologic fracture and nonunion of the clavicle in the radiation field.

Case Histories
During September 1999 three patients presented to the musculoskeletal tumor service with painful nonunions of the clavicle. All three patients had undergone radiotherapy for neoplasms in the past. The radiation fields in all cases included the area of fracture, and radiation was delivered with curative intent at near-maximal doses. All patients had secondary radiation changes, and two also had previous surgical removal of soft tissues at or adjacent to the clavicle.

Patient A is a 61-year-old male who 10 years previously underwent a laryngectomy, left radical neck dissection, and tracheostomy for invasive squamous cell carcinoma of the larynx. He was then treated with “maximum dose” radiation to the neck and adjacent lymph nodes and soft tissues, and is free of disease. The left clavicle, sternum, and ribs were fractured in a motor vehicle accident (MVA) in January 1999. The sternum and ribs healed, but the clavicle went on to a painful nonunion.

Patient B is a 70-year-old osteoporotic female who, in 1967, underwent radical mastectomy for breast cancer. She then underwent a 30-day cobalt radiation treatment to the left chest wall and axilla including the region of the left clavicle. She has been free of disease since that time, although her arm function was significantly compromised by post-radiation lymphedema. Onset of clavicle pain in June 1999 prompted an X-ray that was negative for fracture. Subsequently, a fracture line developed and showed no radiographic or clinical healing over four months. The patient wanted surgery, but refused autogenous bone graft. She also refused the use of growth factor-laden material due to concerns about

Surgical Treatment of Post-Radiotherapy Nonunions of the Clavicle
Glenn Wera, M.D., David Glenn Mohler, M.D., and Loretta Chou, M.D.

Glenn Wera, M.D., is in the Department of Orthopaedics at Case Western Reserve University, University Hospitals of Cleveland, Cleveland, Ohio. David Glenn Mohler, M.D., is an Assistant Clinical Professor in the Department of Orthopaedic Surgery and Sports Medicine, Stanford University Medical Center, Stanford, California. Loretta Chou, M.D., is an Assistant Professor in the Department of Orthopaedic Surgery and Sports Medicine, Stanford University Medical Center, Stanford, California.

Correspondence: Glenn Wera, M.D., Department of Orthopaedics 11100 Euclid Avenue, Cleveland, Ohio 44106.
potential carcinogenic effects.

Patient C is a 61-year-old male who underwent chemotherapy and high-dose radiation treatment for non-Hodgkins lymphoma (NHL) in the region of the clavicle during 1982. He fractured the left clavicle nine years prior to surgery and developed a painful nonunion. Multiple surgeons had refused operation due to the poor tissue quality and the patient’s insistence on avoiding autogenous bone graft.

Materials and Methods

All patients underwent open reduction internal fixation with different techniques appropriate to their clinical situation and respecting their individual treatment constraints. All patients were operated upon by the senior author (DGM). Titanium was used exclusively to maximize the utility of any future magnetic resonance imaging. To prevent vascular injury and allow the hardware to remain permanently fixed, blunt tipped, non-self-tapping/self-drilling screws were used and all screw tips were kept at but not through the cortex. Perioperative intravenous antibiotics followed by oral antibiotics were used for 72 hours in all cases. Skin sutures were left for three weeks. Slings were used for 6 weeks, except for daily showers. Pendulum exercises were begun at day two and passive motion under physical therapy guidance was instituted between weeks 3 and 4 following radiographs negative for loss of reduction. Active range of motion was instituted at 6 weeks in all cases following a second radiograph confirming solid fixation.

Two patients were evaluated at 9 and 28 months after surgery (patients B and C). Patient A was evaluated 9 months postoperatively but died before the 2-year follow-up. Radiographs were taken in the anterior-posterior plane and at 20° cephalad view in order to assess evidence of fixation failure and nonunion. Outcome testing was performed using the Constant-Murley shoulder score and the Simple Shoulder Test. We chose the Constant-Murley method to assess shoulder function because it thoroughly accounts for pain, lifestyle, range of motion, and power using physical examination and questioning. Moreover, it was easy to use in the clinical setting and has been shown to produce low intraobserver and interobserver score differences by Conboy and colleagues. The Simple Shoulder Test was also used to evaluate the status of these patients postoperatively because it was found to produce similar results compared to other popular shoulder rating systems. The Simple Shoulder Test system is a 12-item questionnaire that also accounts for pain, range of motion, daily activity, and power. Both shoulder assessments give a numerical percentage score with one hundred representing normal and full function.

Operative Techniques

Patient A

This patient had radiation effects consisting of thin, desquamating pigmented skin, and a tracheostomy im-

mediately adjacent to the operative area. After careful draping and preparation of the operative site, an incision was made inferior and parallel to the left clavicle and carried deep to the platysma muscle. A full thickness flap was then developed superiorly, exposing the nonunion of the clavicle. The pseudoarthrosis was taken down with rongeurs. A burr was used to cut a slot into the anterior cortex of the two bone ends for the placement of an inlay bone graft. Reduction was then carried out. Iliac crest bone graft was harvested and converted to match sticks and cancellous slurry. The bone graft was placed in the slot, traversing the nonunion site. An inter-fragmentary screw was placed in a lag fashion to hold the reduction and compress the bone ends. A ten-hole 3.5 mm titanium dynamic compression plate was cut down to nine holes, contoured, and fixed with screws. Screw tips were manually checked for protrusion from the inferior clavicular surface. The remaining autogenous bone graft was placed around the nonunion site. Grafton® (Osteotech, Inc., Eatontown, NJ) demineralized bone matrix (DBM) was added around the site of nonunion. Soft tissues were closed in multiple layers followed by small, closely placed skin staples with perfect dermal alignment. Antibiotic ointment was applied to the staple line prior to covering with an occlusive sterile dressing.

Patient B

This patient was very thin, osteoporotic, and had a relatively short medial clavicle segment allowing no more than three screws for fixation in the medial fragment. In addition, she did not want the plate removed, a procedure commonly performed to avoid late subclavian artery disruption from pulsation against prominent screw tips. She had previously had all muscle tissue removed from the clavicle as part of her radical mastectomy. To accomplish fixation with these constraints, an anterior plate placement was planned, with supplemental methylmethacrylate to reinforce the short medial clavicle segment. An inferior incision was made and a full thickness flap was raised. The nonunion site was rongeured to remove all the fibrous tissue. The canal of the medial portion of the clavicle was reamed using a curette to remove all fibrous tissue. Bone cement was mixed with methylene blue. The cement was injected into the medial clavicle to provide additional purchase for screw fixation in the short, extremely osteoporotic bone. A 9-hole plate was contoured to match the anteromedial aspect of the clavicle and curved around the lateral anterior-superior aspect. The medial screws were placed first. Care was taken to avoid prominent screw tips at the far cortex of the bone, which could potentially erode into vessels or the pleura. After placement of the three medial screws, the fracture was reduced. Gaps in the nonunion site were filled with allograft cancellous bone chips prior to placement of the lateral fragment screws in compression. Ad-
ditional allograft was packed around the nonunion site. DBM was not used due to the patient’s concern about the impact of growth factors on possible tumor genesis. The wound was closed in three layers. Wound closure strips were placed over the wound followed by nitro paste with the intention of enhancing skin perfusion and preventing wound edge necrosis in this compromised tissue.

**Patient C**

An inferior full-thickness flap was developed and the nonunion exposed. Fibrous tissue was removed from the nonunion site. Extra bone at the fracture ends was removed piece-meal with a rongeur and set aside for use as bone graft. The fracture was reduced and a lag screw was placed for initial stabilization. Next, a 3.5 mm 10-hole dynamic compression plate (DCP) was applied and fixed with screws. The morselized bone from the clavicle ends was placed at the fracture site. At the fracture site 5 cc of Grafton® putty was used to complement fracture healing. The deep layer was closed with 2-0 chromic sutures. Once this was done, the skin was closed with running 3-0 Prolene suture, wound closure strips, and a sterile dressing.

**Results**

At a minimum of 28-months follow-up, patients B and C were pain free with daily activities. However, Patient A still expressed some discomfort during sleep at 9 months. Patient A died due to liver and renal failure secondary to ethanol abuse 22.5 months after surgery. A telephone interview with the patient’s spouse indicated that his clavicle and shoulder function were absolutely unchanged since his 9-month follow-up evaluation at our clinic. Radiographs taken at 9-months follow-up showed no loss of fixation, plate lift-off, or lytic changes around the hardware (Figs. 1, 2 and 3). Two of three fracture lines have disappeared (Figs. 1 and 3), while the third (Fig. 2) could not be evaluated because of plate placement and the cement artifact. At 28-months postoperatively, patients B and C were re-imaged with

**Figure 1** Radiographs of Patient A, left clavicle. From top to bottom: preoperative, postoperative, and 9-month follow-up. A bony union is apparent at 9 months. Note the lack of protrusion of screw tips in the region of the great vessels.

**Figure 2** Radiograph of Patient B, left clavicle. From top to bottom: preoperative, postoperative, and 9-month follow-up. Fracture line in the medial clavicle is seen on the top radiograph. Bony union cannot be confirmed due to cement artifact. Note anterior placement of plate and screws to avoid the great vessels and obviate the need for plate removal.
Assessment of shoulder function is shown in Table 1. No patients had normal shoulder function on the left, fractured side. However, all patients subjectively felt they had returned to pre-fracture function, and were pleased with their outcome.

In Patient A, inferior subluxation, pain, and instability have been eliminated. The bone has united according to radiographic examination. He was the only patient to have some pain in the shoulder at his last follow-up. This patient had some mild discomfort at night only. The remaining shoulder deficit (Table 1) of the affected limb is a result of radical neck dissection which included removal of substantial amounts of muscle including deltoid, trapezius, and sternocleidomastoid.

In Patient B, clicking pain was eliminated. However, poor forward flexion and abduction persisted as a consequence of pre-existing chronic lymphedema. The affected limb is heavy and weak distal to the shoulder resulting in low assessments of shoulder function. Her Constant-Murley score decreased at 28 months compared to 10 months due to loss of power secondary to lymphedema and disuse (Table 1).

In Patient C, tenting of the skin was eliminated. The patient has a history of bilateral rotator cuff injury accounting for the reduced shoulder scores in both shoulders (Table 1). However, the right shoulder exhibited a better assessment due to successful shoulder arthroscopy performed on that side before ORIF of the clavicle. His Constant-Murley Score and Simple Shoulder Test, which improved at 28 months compared to 10 months after surgery, were attributed to conditioning that included frequent golf and vehicle maintenance. Remarkably, the patient was thrown from a motorcycle at an estimated 40 miles per hour approximately 6 months after surgery. He suffered no major injuries or re-fracture of the affected clavicle.

**Discussion**

The deleterious effects of ionizing radiation on bone are well documented in both animal models and clinical studies. In a rat model, long bones of the appendicular skeleton

### Table 1  Details of Three Patients with Nonunion of the Left Clavicle Secondary to Radiation Treatment

<table>
<thead>
<tr>
<th>Patient, Gender, Age</th>
<th>Immediate Cause, Age</th>
<th>Radiation Treatment</th>
<th>Symptoms</th>
<th>Duration of Nonunion</th>
<th>Constant-Murley Shoulder Score Right:Left</th>
<th>Simple Shoulder Test Right:Left</th>
<th>Nonunion Healed</th>
<th>Fixation Failure</th>
<th>Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 61M</td>
<td>MVA, Max Larynx 1980s</td>
<td>Inf. Subluxation, Pain, Instability</td>
<td>8 mos.</td>
<td>10 mos.: 90:66</td>
<td>10 mos.: 100:83</td>
<td>Yes</td>
<td>No</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>B 70F</td>
<td>Unknown, 30 days CA Breast 1967</td>
<td>Clicking pain, Poor motion forward flexion abduction</td>
<td>4 mos.</td>
<td>10 mos.: 95:47</td>
<td>10 mos.: 100:33</td>
<td>Yes</td>
<td>No</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>C 61M</td>
<td>Re-fracture, Non-Hodgkins Lymphoma 1982</td>
<td>Tenting skin, Pain</td>
<td>9 years</td>
<td>10 mos.: 86:88</td>
<td>10 mos.: 92:67</td>
<td>Yes</td>
<td>No</td>
<td>None</td>
<td></td>
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showed increased risk of fracture following doses of 5,000 rads or greater. Biochemical and histological markers of healing eventually recover to levels no different from controls in irradiated rat femurs. Nevertheless, the negative effect of radiation on bone has been demonstrated to cause long-term weakness and delayed fracture healing in rats. This persistent impairment of the bone repair mechanisms is demonstrated by our patients’ initial inability to heal their clavicle fractures despite the interval of as much as 22 years between radiation and fracture (Table 1).

In one patient, fracture occurred in the absence of a known traumatic event. Rat femurs have been shown to fracture spontaneously after high-dose irradiation. Healed fracture callous in irradiated bone was weaker and less mature at all radiation exposure levels. The strength of the final bony union remained less than the control for all the experimental subjects. Clinical studies show bone subjected to high-dose radiation demonstrates an increased incidence of delayed union and nonunion, and an increased incidence of fracture and re-fracture. A recent report indicated that the surgical removal of periosteum may dramatically increase fracture risk in irradiated bone.

Fractures of the clavicle are common and most unite without the need for surgery. In a large group of 242 subjects with displaced mid-shaft clavicle fractures, open reduction and internal fixation resulted in improved outcomes compared to closed treatment. When nonunions occur and are left untreated, soft-tissue problems, contractures, and decreased range of motion commonly result. Among clavicle nonunions not involving radiotherapy, decortication with plate osteosynthesis proved both to be a reliable and lasting solution. The combination of plating and bone grafting of painful clavicle nonunions produces the highest rates of union with minimal complications. Wu and associates found surgically treated clavicle nonunions to have lower rates of successful union than nonunions of other bones. This reduced healing propensity is ascribed to poor vascularity and a sparse soft tissue envelope. In our cases, surgical removal of surrounding soft tissues for tumor treatment and soft tissue injury from radiation exposure exacerbates this problem.

Each of the patients in this study underwent significant radiation therapy for cancer before suffering chronic, persistent, nonunion of the clavicle. Gainor and coworkers reported on patients with long bone fractures after radiation treatment of metastases. Although such patients suffer from weakened bone and retarded healing rates, internal fixation improved the rate of fracture union by 23% compared to cast immobilization. All fractures in bones that received 3,000 rad or more developed nonunion if treated without surgery. Given that all our patients received doses of at least this amount, nonunion was the expected outcome for their fractures.

In approaching these specific patients, the surgical technique was adjusted to address the mechanical and biological problems inherent in the radiated cancer survivor. First, incisions were placed to avoid tension areas and to be at a distance from the plate and clavicle prominence. In this fashion, any skin healing problem would not expose the hardware or bone. Flaps were kept full thickness to maximize skin vascularity and prevent edge necrosis. Titanium was selected instead of stainless steel to allow the use of magnetic resonance imaging with minimal artifact. Because of the weakened bone, plate lengths to allow eight or more cortices of fixation on each side of the fracture were selected. In addition the plates are meant to be permanent, as re-fracture after removal would be likely, and further surgery in a radiated area is to be avoided whenever possible. Plate placement, screw lengths, and orientation were designed to avoid problems with plate erosion through skin and vascular injury from pointed, prominent screw tips. In one case (Patient B) with a medial fracture and osteoporosis, the medial fragment was filled with methylmethacrylate cement to increase the pull-out strength of the screws and enhance rigidity. The bone ends at the nonunion were freshened and contoured to allow maximum intimate contact, and compression was applied through the use of lag screws and dynamic compression plates. Biologic enhancement of the fracture repair process was achieved through the use of iliac crest bone graft, allogeneic growth factors, allograft cancellous bone, or combinations of these where possible. Skin and soft tissue closures were done meticulously, and antibiotics were continued past the perioperative period to prevent bacterial invasion through the slow-healing skin layers.

The patients’ radiographic results indicate successful union. Although fracture lines are no longer visible, it is very hard to evaluate presence or absence of fracture lines after grafting and plating. The lack of pain and the absence of any plate lift-off or lysis around the screws at 9 and 28 months after surgery is good evidence that the patients have healed.

Functional assessment through the use of scoring systems is problematic in this population. All three patients had functional deficits independent of their clavicle nonunions. Two had substantial soft tissue resections as part of their cancer treatment and the third patient had bilateral rotator cuff pathology. The Constant–Murley score and Simple Shoulder Test reflected that the patient’s shoulders were stable, strong, and mobile. Both systems are based on a percentage of normal function. Although they did not result in equal scores, the comparison of the affected limb to unaffected limb was consistent in all three subjects. The largest difference stemmed from the fact that the Constant–Murley system’s score for power involved measuring the ability of a patient to resist force during abduction whereas the Simple Shoulder Test questioned the patient’s ability to throw a ball in over and under hand fashions. It also assessed power by questioning the patient’s ability to carry three different weights.
at three different positions. Otherwise the assessment for range of motion, pain, and physical activity including work and leisure were very consistent. All patients improved their shoulder function postoperatively and approached the performance level of their unaffected limb. Patient A had a lasting deficit of shoulder function due to previous radical neck dissection for laryngeal cancer, with resection of the anterior deltoid, trapezius, and sternocleidomastoid. Accordingly, range of motion was decreased, manifesting in low scores according to both methods of assessment (Table 1). No weakness could be attributed to the ORIF of the affected clavicle. Patient B had lasting deficit of the affected limb due to persistent lymphedema stemming from her radiation treatment for breast cancer. Consequently, the affected limb demonstrated a poor range of motion that lowered both shoulder scores. Disuse of the affected limb lead to loss of power and lower scores at 28 months compared to her 10-month assessment. However, this deficit was not a consequence of ORIF of the affected clavicle. Patient C had some performance deficit of the affected limb due to bilateral rotator cuff injury. Although he had undergone successful arthroscopy of the right shoulder, we assessed both shoulders as approximately equal at the 10-month assessment. This result suggests that the affected left shoulder function was completely restored outside of the rotator cuff injury. This patient has an active lifestyle that includes both golf and automobile maintenance. His improved shoulder scores at 28 months are attributed to gains in power stemming from lifestyle-related conditioning. The fact that this patient suffered a motorcycle accident that did not result in re-fracture attests to the viability of ORIF of the clavicle in these patients. All patients reported significant relief of pain and improved range of motion at last follow-up.

Conclusion

This study describes methods to achieve excellent outcomes in treating radiated clavicle nonunions. Rigid, long plate fixation supplemented with autogenous iliac crest bone graft and careful soft tissue management is the preferred method of treatment. Successful outcomes can be achieved with modifications of this ideal.

References