Treatment of Delayed and Nonunited Fractures and Osteotomies With Pulsed Electromagnetic Field in Children and Adolescents

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abstract

Nonunion of fractures or osteotomies in the pediatric population is rare. The gold standard for the treatment of nonunions involves harvesting autologous iliac crest bone graft and sometimes internal fixation, which are invasive procedures. The purpose of this study was to evaluate the effectiveness of pulsed electromagnetic field on a nonunited fracture or osteotomy in the pediatric population.

A retrospective study was performed on all patients at the authors’ institution who used pulsed electromagnetic field as part of their treatment for nonunion or delayed union. Success of the initial nonunion treatment was defined as complete union of the fracture or osteotomy site. Two types of treatment were administered once delayed bone healing was identified: pulsed electromagnetic field alone or pulsed electromagnetic field plus an adjunct treatment. Twenty-one patients were included; 8 osteotomies and 14 fractures developed a nonunion. Average patient age was 11.7 years. Average age for patients who healed with the initial treatment was 10.7 years, whereas nonhealers had an average age of 14 years. Eighty-nine percent of osteotomy nonunions healed with their first management. Fifty-seven percent of fracture nonunions healed at the first attempt.

The use of pulsed electromagnetic field is a good option for the initial treatment of pediatric nonunions, especially for patients who develop nonunions secondary to osteotomies. Adding bone marrow aspiration improves the outcomes and is minimally invasive compared with autologous iliac crest bone graft, with no complications.
Nonunion of fractures or osteotomies in the pediatric population is rare.\textsuperscript{1-4} The thicker periosteum found in younger patients makes them less prone to develop nonunions. Delayed union is defined in adults as a healing time of more than 12 weeks. However, no standard description exists of delayed or nonunion in the pediatric literature. Nonunion in children has been quoted as healing delayed beyond 10 weeks.\textsuperscript{4}

The gold standard for the treatment of nonunions involves harvesting autologous iliac crest bone graft.\textsuperscript{3-5} However, this method is invasive and associated with a high rate of complications, most commonly persistent donor-site pain.\textsuperscript{6} Some fractures also require internal fixation to stabilize the injury.\textsuperscript{7} This involves an additional procedure to remove the implants in children.

At the authors’ institution, pulsed electromagnetic field has been used as the first line of treatment for nonunion for osteotomies and fractures. This noninvasive method enhances bone healing. To the authors’ knowledge, no studies have reported the use of pulsed electromagnetic field in the treatment of pediatric nonunions. The purpose of this study was to evaluate the effectiveness of pulsed electromagnetic field on a nonunited or delayed fracture or osteotomy in the pediatric population.

**Materials and Methods**

Institutional Review Board approval was obtained to perform a retrospective database search from July 2002 to June 2009 at a single orthopedic practice on all patients who used pulsed electromagnetic field as part of their treatment. Nonunion was defined as a lack of fracture healing progression on sequential radiographs or no evidence of healing more than 10 weeks following the injury.\textsuperscript{4} Delayed union was defined as no evidence of callus progression on sequential radiographs. Medical records for all patients were reviewed. The collected data included type of injury that led to nonunion (ie, fracture or osteotomy), patient age when treatment began, and treatment type recommended to the patient once a delayed union or a nonunion was identified.

Inclusion criteria were patients younger than 16 years with documented delayed or nonunion and the use of pulsed electromagnetic field as part of the treatment plan. Success of the initial nonunion treatment was defined as complete union of the fracture or osteotomy site. The latest follow-up was at least to nonunion consolidation. The fracture or osteotomy site was considered united when 4 cortical bridges were present or the nonunited area was described as healed in the medical records. The time of healing or failure was determined from the time the pulsed electromagnetic field was prescribed to cortical healing or to the need to use an additional procedure. Failure was described as persistent nonunion of the fracture or osteotomy site resulting in a secondary procedure. Patients lost to follow-up, older than 16 years, and treated with pulsed electromagnetic field for other reasons were excluded. Patients with pathologic fractures, stress fractures, or refractures were also excluded (n=4).

Two types of treatment were administered once a nonunion was identified: pulsed electromagnetic field alone or pulsed electromagnetic field plus an adjunct treatment. Adjunct treatment was anterior iliac crest bone marrow injection or autologous iliac crest bone graft application with or without fixation. All patients were instructed to use the pulsed electromagnetic field for 10 hours a day as part of their treatment regimen. Bone marrow aspiration or injection was considered a minimally invasive procedure because all were performed percutaneously. Three- to 4-mL aliquots were drawn from different bony sites through the same skin entry point to obtain a total of 12 to 15 mL per procedure.\textsuperscript{7}

**Results**

**All Patients**

Twenty-one patients were included; 1 patient had a bilateral osteotomy. Eight osteotomies and 14 fractures developed a nonunion (Figures 1, 2). Average patient age was 11.7 years (range, 3-15.7 years). Average age was 13 years in the fracture group and 9.6 years in the osteotomy group. Pulsed electromagnetic field alone was used in 17 limbs, and 5 limbs had some type of adjunct used (4 bone marrow injections and 1 injection with nail dynamization). Average follow-up from the moment pulsed electromagnetic field was administered was 12 months.

Nonunion or lack of fracture improvement was diagnosed at an average of 19.6 weeks (range, 9.1-42 weeks) (Figure 3). One patient was less than 10 weeks from fracture or osteotomy at the time of delayed union diagnosis. He was a 4-year-old with myelomeningocele who underwent bilateral distal tibia osteotomies.

**Figure 1:** Anteroposterior radiograph of an 11-year-old patient showing a displaced distal radius fracture.

**Figure 2:** Anteroposterior (A) and lateral (B) radiographs of the distal radius after open reduction and internal fixation.
One osteotomy was diagnosed with an infection of the pin tracts with lack of union progression. This patient developed a wound dehiscence and an infected nonunited osteotomy by 4 weeks. The other leg developed a methicillin-resistant Staphylococcus aureus infection from otitis media at 6 weeks. He underwent pin removal, intravenous antibiotics, whirlpool therapy, and then casting once the wound had healed, with pulsed electromagnetic field for the nonunion.

Twelve (71%) of 17 nonunions treated with pulsed electromagnetic field only healed at an average of 15.8 weeks (100% [6/6] in the osteotomy group and 55% [6/11] in the fracture group) (Figure 4). Three of 4 (75%) patients treated with pulsed electromagnetic field and adjunct treatment healed at 19.8 weeks (50% [1/2] in the osteotomy group and 100% [2/2] in the fracture group). Therefore, 68% (15/22) healed after initial treatment with minimally to noninvasive techniques at an average of 15.8 weeks. The patient treated with pulsed electromagnetic field, injection, and dynamization did not heal due to poor fixation that eventually required an exchange for a more rigid nail.

Average age for patients who healed with initial treatment was 10.7 years, whereas the nonhealers had an average age of 14 years (range, 12.8-15.5 years). All patients younger than 12 years healed after the first attempt (n=6). All patients who failed to unite with pulsed electromagnetic field alone or with an adjunct healed with a secondary procedure. Those treated with a secondary procedure healed 12 weeks (range, 9-16 weeks) after the secondary procedure.

**Osteotomy Group**

Eighty-eight percent (7/8) of osteotomy nonunions healed after the first treatment (6/6 with pulsed electromagnetic field only and 1/2 with bone plus added bone marrow injection). Average time to healing was 18.8 weeks (range, 7-39 weeks). One patient required a second open procedure and bone grafting to successfully heal the osteotomy. Therefore, 88% of nonunited osteotomies healed with minimally to noninvasive procedures. Four (50%) osteotomies were tibial derotation osteotomies. A proximal femoral osteotomy required a second procedure. Autologous iliac crest bone graft was used to augment after a failed attempt with bone marrow injection and pulsed electromagnetic field.

**Fracture Group**

Fifty-seven percent (8/14) of fracture nonunions healed after the first treatment (6/11 with pulsed electromagnetic field only, 2/2 with pulsed electromagnetic field plus bone marrow injection, and 0/1 with pulsed electromagnetic field with nail dynamization). Average time to healing was 13.2 weeks (range, 6-22 weeks). Four (29%) fractures were open. Three of the 4 open fractures had been treated originally with fixation and healed with pulsed electromagnetic field alone or with bone marrow injection. The open fracture that did not unite despite pulsed electromagnetic field had been casted and healed with fixation, pulsed electromagnetic field, and injection. All persistent nonunions healed after a second surgical procedure, including internal fixation (n=2), fibular osteotomy (n=2), and nail exchange (n=2). Therefore, 57% of nonunited fractures healed with minimally to noninvasive procedures.

**Complications**

No patients who underwent bone marrow aspiration or injection presented any type of morbidity from the harvested or grafted sites. No complications occurred with the use of pulsed electromagnetic field. No patient reported persistent pain when open bone graft procedures were performed. No compliance issues were detected in the clinical notes because the use of the pulsed electromagnetic field occurred during sleeping hours, which anecdotally was well-tolerated by the patients.

**Discussion**

Two studies have evaluated delayed unions or nonunions following fractures in children. This complication is rare. The current authors found no report addressing the treatment of nonunion following osteotomy in children. The most common causes of nonunion or incomplete bone healing in children are comminuted or open fractures, severe soft tissue loss, infection, fractures undergoing open reduction and internal fixation, and inadequately fixed fractures. In the adult literature, delayed union has been defined as a healing time of 12 weeks or more. However, no standard description exists of delayed or nonunion in the pediatric literature. Greenbaum et al reported that fractures in children younger than 9
years unite sooner. As a result, they defined a delayed union in children as impaired healing at 10 weeks. In the current study, the time to diagnose a nonunion or delayed union was more than 10 weeks in all but 1 patient. This patient was treated before due to infection of his osteotomy that showed no progression of bone healing. Therefore, the diagnosis of nonunion in children should be made at 10 weeks following the inciting event.

Schrader et al\textsuperscript{2} reviewed 43 pediatric nonunions. When comparing diaphyseal vs elbow nonunions, diaphyseal nonunions had a shorter mean time to bony union (9 vs 11 months, respectively). Schmittenbecher et al\textsuperscript{1} reported a delayed union rate of 1.9\% in pediatric forearm fractures treated with elastic intramedullary nails. All of these ultimately healed within 13 months. Although the current authors agree that most of these delayed unions and nonunions may eventually heal, it seems unreasonable to prolong closed treatment in a cast for such a long time in lieu of minimally or noninvasive treatment. Avoidable and unnecessary joint stiffness from prolonged casting is another factor that influences the decision to act earlier. The authors’ institution offers both types of treatment.

Pulsed electromagnetic field has been used successfully in the adult population.\textsuperscript{8,9} One report exists in the literature of an isolated case of a nonunited lateral condyle fracture treated by this method.\textsuperscript{10} Other reports describe using pulsed electromagnetic field in animal models.\textsuperscript{11,12} These studies demonstrate less bone volume loss, faster recovery of load bearing, increased new bone formation, and higher mechanical strength compared with the control side. Abdelrahim et al\textsuperscript{13} reported similar findings when comparing mandible fractures treated with and without the use of pulsed electromagnetic field; those treated with pulsed electromagnetic field showed better bone mineral density and stronger healing.

To the authors’ knowledge, the current study is the first to examine pulsed electromagnetic field for the treatment of pediatric fracture or osteotomy nonunions. Schnoeke and Midura\textsuperscript{14} examined the phosphorylation kinetics and signaling pathways induced by pulsed electromagnetic field and compared the intensity with that induced by other known anabolic agents parathyroid hormone and insulin. The authors found “that exposure of bone cells to PEMF [pulsed electromagnetic field] induce immediate intracellular signal transduction events consistent with those associated with anabolic bone cell responses.”\textsuperscript{14}

The effective dosage treatment of pulsed electromagnetic field for fracture nonunions has been studied. The reported success rate was 35.7\% for patients who used the device less than an average of 3 hours a day and 80\% for patients who used the device for more than 3 hours a day.\textsuperscript{15} The patients in the current study used the device approximately 8 to 10 hours per day (during sleep) as recommended by the manufacturer.

Nolte et al\textsuperscript{16} and Rutten et al\textsuperscript{17} reported the treatment results of using low-intensity pulsed ultrasound on nonunions. Rutten et al\textsuperscript{17} reported healing rates over 70\%. The current study’s success rate with this device was 71\% when used initially without the need to perform open bone graft.

Connolly\textsuperscript{18} reported his experience with various forms of electrical stimulation and evaluated how to select which type of nonunited fractures would be appropriate for surgical intervention, electrical stimulation, or no treatment. Although he was unable to justify a firm conclusion due to the small size, he concluded that electrical stimulation does not compensate for inadequate fracture fixation. This may have been the case in the current study’s fracture patients because 43\% of them required fixation or revision of the fixation, whereas 88\% osteotomies healed after pulsed electromagnetic field alone or with bone marrow injection. The osteotomy patient that required a second procedure healed with adding bone graft to the osteotomy site.

Several studies report on the technique and effectiveness of bone marrow injection.\textsuperscript{7,19,20} Connolly et al\textsuperscript{1} treated 20 nonunited tibial fractures with bone marrow injection and adequate fixation. Half of the patients were treated with casts and the other half with intramedullary nails. Eighteen of the 20 tibial fractures healed, with the 2 nonunited fractures occurring in the cast immobilization group. The authors recommended aspirating between 1- to 5-mL aliquots at a time because continued aspiration draws off mainly venous blood.\textsuperscript{7} Aspirating twice from the same location decreases cell counts of mononuclear cells and mesenchymal stem cells in the second aspirate; however, it does not affect the biological characteristics. Although an increased aspiration volume higher than 8 mL reduced the cellular concentration, the admixture of peripheral blood did not affect the biological characteristics.\textsuperscript{7}

The current authors considered the use of a noninvasive treatment method, such as pulsed electromagnetic field, to avoid the morbidity associated with harvesting autogenous iliac crest bone graft, which is the gold standard. Conway\textsuperscript{21} compared the use of iliac crest bone graft (anterior and posterior) with intramedullary canal grafting. He found that iliac crest grafting had donor-site complications, such as nerve injury and persistent pain. Intramedullary canal grafting resulted in the fewest complications. No patient in the current study who underwent bone marrow aspiration or injection or open grafting presented any type of morbidity from the harvested or grafted sites.

In a series of 208 patients undergoing iliac crest bone graft harvest for anterior lumbar interbody fusion, 41\% reported pain at 6 months, 33\% at 1 year, and 31\% at 24 months.\textsuperscript{6} No significant differences existed between the anterior and posterior harvest sites or bicortical grafts. However, when Ahlmann et al\textsuperscript{22} compared anterior and posterior iliac crest bone graft harvest, they found that postoperative site
pain was significantly more severe and of longer duration after anterior harvest. The increased complication rate with anterior harvest was likely due to the increased risk of nerve injury and subsequent numbness (lateral femoral cutaneous nerve). Other studies have shown similar results following iliac crest bone graft harvest.21-25

The current study had some limitations. The number of patients was low; therefore, no statistical significance could be established. However, the authors reported their observations with 2 treatments. Also, the definition of nonunion in children is not clearly established in the literature. No patient was metabolically screened to assess nutrition or calcium or vitamin D content. There was no way to know whether the patients were fully compliant with the pulsed electromagnetic field. Finally, no control group existed with which to compare the study group. Some may argue that a patient can be kept in a cast for as long as 6 months prior to calling such a fracture or osteotomy nonunited. In the authors’ institution, this seems unreasonable because other minimally invasive modalities exist to help patients.

CONCLUSION
The use of pulsed electromagnetic field is a good option for the initial treatment of pediatric nonunions, especially for patients who develop nonunions secondary to osteotomies. It is noninvasive and demonstrates no long- or short-term morbidity. Adding bone marrow aspiration improves outcomes and is minimally invasive when compared with autologous iliac crest bone graft, with no complications. However, the source of the nonunion and the fixation stability should be carefully scrutinized, especially in fracture cases, because some of these may benefit from a more rigid immobilization. If evidence exists of poor fixation, pulsed electromagnetic field will not be necessary, and a revision of the fixation should be performed to enhance stability.  

REFERENCES