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● *Clinical Note*

SHOCK WAVES IN THE TREATMENT OF STRESS FRACTURES

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Abstract—In soccer players, lower extremity stress fractures are common injuries and are the result of repetitive use damage that exceeds the intrinsic ability of the bone to repair itself. They may be treated conservatively but this may cause long-term complications, such as delayed union, muscle atrophy and chronic pain. Stress fractures that fail to respond to this management require surgical treatment, which is also not without risks and complications. Extracorporeal shock wave therapy (ESWT) has been used successfully on fracture complications, such as delayed union and nonunion. As such, we want to examine ESWT in the management of stress fractures. In this article, we present a retrospective study of 10 athletes affected by chronic stress fractures of the fifth metatarsus and tibia that received three to four sessions of low-middle energy ESWT. At the follow-up (8 wk on average), the clinical and radiography results were excellent and enabled all players to gradually return to sports activities. These reports show that ESWT is a noninvasive and effective treatment for resistant stress fractures in soccer players. (E-mail: b.moretti@ortop2.uniba.it (B.M.), angelanotarnicola@yahoo.it (A.N.)) © 2009 World Federation for Ultrasound in Medicine & Biology.

Keywords: **Stress fracture, Shock waves therapy, Soccer player, Middle energy.**

INTRODUCTION

The term ‘‘stress fracture’’ was first used in sports medicine in 1958 (Devas 1958) but it was originally detected as early as 1855 as a ‘‘march fracture’’ in soldiers (Breithaupt 1855). At present, this injury causes concern among soccer players at all levels, though it accounts for just two percent of all soccer injuries (Raasch and Hergan 2006).

The tibia is the most common location for stress fractures, followed by the second and the fifth metatarsals, the fibula, the femur and the hip (Bennell et al. 1997).

When treating this type of injury, we must bear in mind that the injury is caused by stress; this stress must, therefore, be eliminated before healing can occur. Healing can take 6 to 8 wk and rest should be part of the treatment. Re-evaluation should monitor pain and include imaging; once the patient is pain-free and has a normal radiograph, a gradual return to training is possible. If more conservative measures fail, surgery is necessary. Overall, although stress fractures may account for a small percentage of the injuries suffered in soccer, they can put players out of action for a long period of time (Warden et al. 2006).

Recently, extracorporeal shock wave therapy (ESWT) has been used in the treatment of a number of musculoskeletal conditions and has shown promising results in attempts to improve fracture healing and delayed union in general (Haupt et al. 1992; Schaden et al. 2001). The rationale underlying the treatment is the bone and vessel growth stimulation by nitric oxide production (Ciampa et al. 2005).

This article reports the outcomes of ESWT in a group of athletes suffering from delayed union or nonunion of stress fractures that were resistant to any other conservative management. The tested method was to use a low-middle energy level to stimulate osteogenesis in stress fractures in which the pathogenesis is a lack of balance between osteoblasts and osteoclasts in favor of the latter.

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MATERIALS AND METHODS

We present here a retrospective study about the treatment of some elite and sub-elite athletes for delayed union or nonunion of stress fractures by ESWT from January 2004 to May 2007. We recruited 10 patients, all male, who ranged in age from 20 to 29 y and actively participated in soccer. Stress fractures had occurred in the metatarsus in six patients and in the tibia in the other four. The patients who sustained injuries to the foot presented with a history of insidious pain, swelling and ecchymosis, which was initially localized in the fifth metatarsal region and then moved to the forefoot and midfoot. Generally, the stress fractures were diagnosed by another specialist some time after the onset of symptoms. The diagnoses were based on clinical history and radiographic films that revealed a radiolucency perpendicular to the long axis of the fifth metatarsal within 1.5 cm of the tuberosity. The primary treatment was the restriction of sports activity and the use of an open toe cast shoe for approximately 3 to 4 wk. One patient underwent internal fixation that involved K-wires placed percutaneously to treat the bone displacement. All of the patients continued to complain of persistent pain and the radiographies showed an absence of union. At this point, they came under our observation, where we subsequently carried out extracorporeal shock wave therapy (ESWT).

The tibial stress fractures were reported as an insidious onset of pain in the mid-anterior leg after a period of intense training. As the trouble progressed, the athletes began to have pain when walking or even at rest. Physical examinations revealed swelling in the anterior proximal region of the leg. Radiographs remained normal for several weeks and then revealed a distinct radiolucency line on the anteromedial portion of the proximal first, second or third of the tibia. The athletes stopped running and jumping for several months before attempting to slowly resume sports activities, but they were forced to stop again due to pain that prevented any activity. Radiographic imaging at this time showed a thickened anterior cortex with a transversal lucent line in the anterior tibia, which was diagnosed as a stress fracture.

Since these athletes were elite and sub-elite soccer players, they needed to return to playing quickly and we, therefore, carried out ESWT. The study was approved by our university ethics committee, and we followed the Declaration of Helsinki ethical principles for medical research involving human subjects. We received informed consent from each athlete to participate in this study. The ESWT was generated by an electromagnetic device (Minilith SL1, Stortz, Switzerland). The skin region was put into direct contact with the shock waves generation tube after applying ultrasound gel and using an ultrasound in-line scanner to identify which side the fracture was on. The therapy was performed without anesthesia. The shock wave intensity was classified as low- or middle-energy so the patient could bear the pain well (range from 0.09 to 0.17 mJ/mm^2) and we administered three sessions of 4000 impulses every 48 h. Injuries to the fifth metatarsus were treated for a total of three sessions, while injuries to the tibia received four applications. After therapy, the patients with metatarsal fractures wore an open toe cast shoe for 6 wk. Patients with tibial fractures were told only to refrain from sports activities such as running and jumping. We monitored the patients by clinical examinations and X-rays during the months following the ESWT.

CASE REPORTS

Case 1

This case involved a 29-y-old male sub-elite soccer player with a stress fracture of the fifth metatarsal base. He had stopped all sports activities and was using a foot cast. Four months after diagnosis of the injury, we observed no clinical or radiographic improvements. We diagnosed the resistant chronic stress fracture and performed ESWT. The dosage administered was 4000 impulses at 0.09 mJ/mm^2 for three applications. After ESWT, we suggested that he wear a foot cast and refrain from playing soccer. Six weeks after treatment, radiography showed consolidation and the pain and tenderness had disappeared. He was able to gradually return to soccer 10 wk after ESWT.

Case 2

A 26-y-old male elite soccer player visited our clinic 4 mo after sustaining a stress fracture of the fifth metatarsal base. He had stopped all sports activities and was using a foot cast but no improvement was noticeable. At this point, we decided to use ESWT. The dosage administered was 4000 impulses at 0.14 mJ/mm^2 for three applications. After ESWT, we suggested total rest from sports and a foot cast. Radiographic consolidation was observed 8 wk after the treatment. He was able to return to full-time sports 3 mo after receiving ESWT.

Case 3

We examined a 25-y-old male sub-elite soccer player suffering from pain in the fifth metatarsus. We diagnosed a stress fracture of the fifth metatarsal base. As chronic nonunion of the fracture had already developed, we performed ESWT. The dosage administered was 4000 impulses at 0.14 mJ/mm^2 for three applications. After ESWT, we suggested that he wear a foot cast and refrain from sports for 6 wk. Radiography showed gradual consolidation. Two months after the initial ESWT, we repeated the treatment. The dosage administered was 4000 impulses at 0.09 mJ/mm^2 for three applications.

For the following 6 wk, the patient played no soccer and used a cast. The radiologic image showed consolidation and union 3 mo after the first ESWT. The player started running again and was able to return to full-time soccer 6 mo after treatment.

Case 4

This case involved a 20-y-old male elite soccer player who experienced sudden pain in his foot while competing in a match. He stopped playing and went to the emergency room. The radiographs showed a stress fracture of the fifth metatarsal base. Rest and a foot cast were recommended. After 3 mo, his foot was still tender and we diagnosed a chronic stress fracture of the fifth metatarsus (Fig. 1). We performed ESWT, administering a dosage of 4000 impulses at 0.11 mJ/mm^2 for three applications. After ESWT, we advised the player to continue to rest and use the foot cast. Six weeks after ESWT, radiographs showed an improvement (Fig. 2) and he did not experience further pain. Four months after receiving ESWT, he returned to soccer.

Case 5

A 28-y-old male sub-elite soccer player came to us with a stress fracture of the fifth metatarsal base. He had suffered an acute injury during a match and was admitted to the hospital. He underwent surgical internal fixation, used a foot cast and stopped sports activities for 8 mo. However, bone union had still not been achieved. We performed ESWT, administering a dosage of 4000 impulses at 0.17 mJ/mm^2 for three sessions. After ESWT, we ordered rest and a foot cast for 6 wk. Radiography showed gradual consolidation. The player was able to return to soccer completely 4 mo after ESWT.

Fig. 1. Case 4: The X-rays image shows a stress fracture of the fifth metatarsal base before extracorporeal shock wave therapy (ESWT).

Fig. 2. Case 4: The X-rays plan shows the bone consolidation at 6 wk after extracorporeal shock wave therapy (ESWT).

Case 6

A 27-y-old male sub-elite soccer player visited our clinic 3 mo after he initially began to suffer from foot pain. Swelling and tenderness of the fifth metatarsus were noticeable and the radiographic diagnosis was a stress fracture of the metatarsal base. He then stopped all sports activities and began to use a foot cast but no improvement was observed. Three months after the initial diagnosis, we carried out ESWT. The dosage administered was 4000 impulses at 0.17 mJ/mm^2 for three sessions. After ESWT, he continued to refrain from sports and use the foot cast. Six weeks after ESWT, bone consolidation was observed on the radiographs. Three months after treatment, fusion was complete and he subsequently returned to playing soccer.

Case 7

A 24-y-old male soccer player stopped sports activities for 10 months because of a stress fracture of the middle third of the tibia. Although he had no acute injury, his mid-anterior leg was painful and swollen. Radiographs showed cortical radiolucency. Ten months after the initial symptoms appeared, we diagnosed resistant chronic stress fracture of the tibia (Figs. 3 and 4) and performed ESWT. The dosage administered was 4000 impulses at 0.11 mJ/mm^2 for four applications. After ESWT, we ordered the player to refrain from sports activities. Radiographic improvement was observed 6 wk after ESWT (Figs. 5 and 6) and he has experienced no pain or tenderness since then. Three months after ESWT ended, the radiographs showed complete consolidation and he returned to soccer full-time.

Case 8

A 22-y-old male elite soccer player came to see us after suffering from pain and swelling of the medial left tibia for 4 mo. He was unable to run and had gradually suspended his soccer-playing activities. By the time of diagnosis, a chronic nonunion of a stress fracture of the middle third of the tibia had already developed. He continued to refrain from all sports activities while we performed ESWT, administering a dosage of 4000 impulses at 0.17 mJ/mm^2 for four applications. When he was reevaluated 6 wk later, he was free from pain and tenderness and the radiographs showed complete consolidation 3 mo after treatment. He was able to return to soccer full-time 4 mo after completion of ESWT.

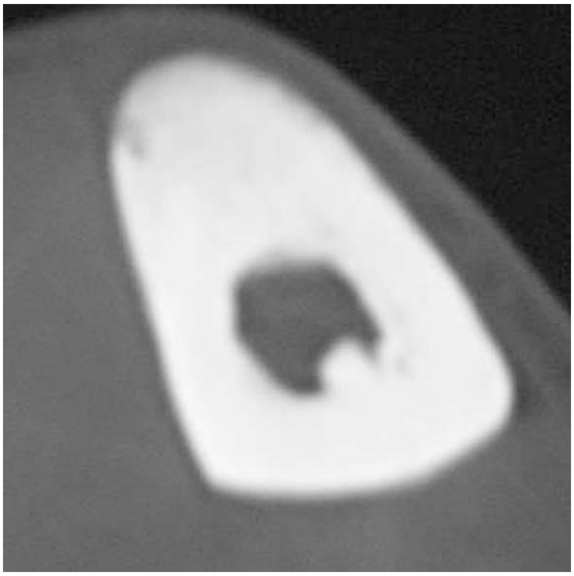

Fig. 4. Case 7: The CT image shows a stress fracture of midanterior tibia before extracorporeal shock wave therapy (ESWT).

Case 9

A 26-y-old male sub-elite soccer player came to see us with a stress fracture of the third proximal of the right tibia. He had abruptly stopped all sports activities 6 mo previously because he felt pain while running and

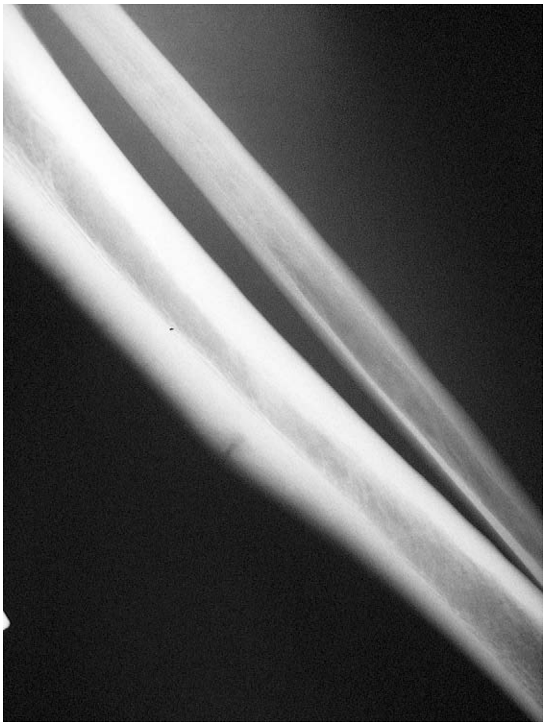

Fig. 3. Case 7: The X-rays image shows a stress fracture of mid-anterior tibia before extracorporeal shock wave therapy (ESWT).

Fig. 5. Case 7: The X-rays plan shows the bone consolidation at 6 wk after extracorporeal shock wave therapy (ESWT).

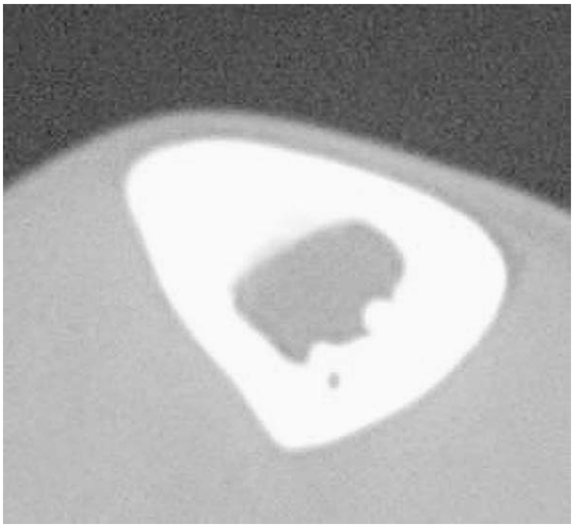

Fig. 6. Case 7: The CT image shows the bone consolidation at 6 wk after extracorporeal shock wave therapy (ESWT).

jumping. The radiographs showed radiolucency through the thickened cortex of the anterior third proximal tibia; we diagnosed recalcitrant chronic stress fracture and performed ESWT. The dosage administered was 4000 impulses at 0.15 mJ/mm^2 for four applications. After ESWT, we ordered the player to continue to refrain from playing soccer. Eight weeks after treatment, radiographic improvement was observed and he was experiencing no pain at rest or while walking. Three months after ESWT was completed, he returned to playing soccer and there has been no recurrence of pain to date.

Case 10

We examined a 19-y-old male elite soccer player suffering from pain and swelling and we diagnosed a stress fracture of the right mid-anterior tibia. He reported having a sudden ache during a match, causing him to stop playing completely. There was no diagnosis for 5 mos. When we visited him, he was diagnosed as having nonunion of the stress fracture at the third middle of the tibia. We performed ESWT administering 4000 impulses at 0.17 mJ/mm^2 for four applications and ordered him to refrain from soccer. Seven weeks after ESWT, radiography showed bone consolidation. After 3 mo, he had no pain and subsequently resumed playing soccer.

RESULTS

The extracorporeal shock waves therapy was well tolerated by all patients. No skin injures or ecchymoses were observed during or after any of the treatment sessions. One patient with the fifth metatarsal fracture needed a second session of ESWT because his clinical and radiographic situation remained unsatisfactory. The patients were also told to use an open toe cast shoe on the metatarsal fractures for 6 wk. We advised all patients to stop sports activities for the 6 to 8 wk following therapy. No complications were observed in any of the 10 cases.

We observed bone fusion on the X-rays at 6 to 14 wk after ESWT. The patients resumed sports activities 3 to 10 mo after treatment without difficulty and with no pain or functional limitation. The radiographic evaluations showed a fully developed bony fusion.

DISCUSSION AND SUMMARY

First detected in Prussian soldiers and reported by Briethaupt in 1855, stress fractures are common injuries in athletes and military recruits. The fracture incidence ranges from as low as 1% to as high as 20% of sports injuries (Matherson et al. 1987; Johnson et al. 1994). They are the result of excessive repetitive loads on the bone that cause an imbalance between the activity of the osteoclasts in bone resorption and the osteoblasts in bone formation (Boden et al. 2001; Noble, 2005; Herrmann et al. 2007). An abrupt increase in the duration, intensity or frequency of physical activity without adequate recovery periods may lead to a stress fracture. Symptoms vary from swelling to insidious pain and a limited ability to walk. Plain radiographs reveal a radio-transparent line in the cortex bone. Stress fractures most commonly involve the tibia and the metatarsal bones, with the fibula, navicula, pelvis and femur being less frequently affected (Bennell et al. 1997; Maitra et al. 1997). Stress fractures are diagnosed by means of the patient's case history, physical examination and imaging evaluation. It is also important to identify and modify any risk factors; moreover, a training regimen and footwear can be easily corrected and intrinsic causes such as nutritional, hormonal or other medical abnormalities need to be addressed. Despite rest, stress fractures can often progress or fail to heal (Young et al. 2006). The traditional therapeutic plan is based on taking a break from all physical activity for 1 to 2 mo, followed by a progressive gradual resumption. However, sometimes these injuries can lead to long periods of inactivity for the athletes and surgical treatment may even be necessary. Furthermore, surgery could cause many complications, including nonunion. (Chang and Harris 1996; De Lee et al. 1983). Researchers are searching for new and efficient therapies that will bring improved results quickly.

The literature is less supportive when it comes to studies that directly address the improved healing process for stress fractures. Rue and colleagues (2004) applied pulsed ultrasound on tibial stress fractures but they observed no significant reduction in healing. The effects of electrical and electromagnetic fields on improving stress fracture healing are not clearly defined. Most studies deal with their effect on delayed unions or nonunions but these studies were not specifically designed to evaluate how effective these therapies are for stress fractures (Benazzo et al. 1995; Retting et al. 1988; Borsalino et al. 1988; Sharrard 1990; Scott et al. 1994).

A shock wave (SW) is a longitudinal acoustic wave that travels through the water of body tissue at ultrasound speed. It is a single pressure pulse with a short needle-like positive spike lasting less than one microsecond at lower amplitudes (Apfel 1982). A SW is known to have a ''cavitation effect,'' which is the phenomenon of microbubble formation from gases that exit in lung tissue. When subjected to ultrasound, they undergo compression cycles of negative and positive pressure and oscillations and this sonodynamic response results in secondary motions, high local shear stress in tissue, microstreaming and implosion (Apfel 1982; Maisonhaute et al. 2002).

Clinicians have used ESWT successfully to break up kidney stones since 1980 and the high efficacy and few adverse effects associated with this treatment have made it the standard of care worldwide. It has also been shown to have a promising effect on the treatment of tendinopathies and on fracture healing (Wang, 2003; Bara and Synder 2007). Unlike the treatment of kidney stones, the main therapeutic goal of orthopedic shockwave application is not to destroy tissue but to stimulate tissue regeneration. Several studies are now researching the methods of bone-growth stimulation that are available for fractures: many articles show that this treatment is effective in reducing the healing time of nonunions (Valchanou et al. 1991; Johannes et al. 1994; Haupt 1997). High energy induces periosteal detachment and trabecular fractures with hemorrhages, which in turn stimulate callus formation and subsequent fracture healing (Narasaki et al. 2003; Bara et al. 2000; Bulut et al. 2006); on the other hand, low-middle energy induces mesenchymal stem cell recruitment and differentiation into osteoblasts for bone formation (Martini et al. 2003; Chen et al. 2004; Aicher et al. 2006).

Taki et al. were the first to report the use of ESWT on five athletes with resistant stress fractures (Taki et al. 2007). The patients in question actively participated in baseball, basketball, soccer or marathons and reported injuries to the middle third tibia, the base of the fifth metatarsal bone, the inferior pubic ramus or the medial malleolus of the ankle. There were four males and one female in that study, ranging in age from 17 to 22 y. All stress fractures were treated conservatively, with the exception of the metatarsal fractures, which were supported surgically by internal fixation. The time interval between the initial symptoms and ESWT ranged from 6 to 25 mo. The shockwave device used was an electro-hydraulic generator and the treatment involved only one application administered under anesthesia using a low number of impulses (2000 to 4000) at high energy (0.29–0.40 mJ/mm^2). Progress after the ESWT was good: clinical absence of pain and radiographic bone consolidation were noted at the follow-ups done 2 to 3 mo after therapy, with the athletes returning to active sports 3 to 6 months after treatment.

The authors suggested that the ESWT should become the first choice for resistant stress fractures among young athletes, where conservative treatment (rest and a cast) can mean long delays before the sports activities can be resumed. However, surgery (intramedullary nailing or internal fixation) is contraindicated in younger patients because it stresses the bone may induce nonunion (Chang et al. 1996; Varner et al. 2005). The authors also recommended follow-up clinical studies to determine the best application protocol for ESWT with regard to energy dosage, the numbers of impulses administered and the amount of application time.

In our study, we treated 10 resistant stress fractures: the patients were male soccer players, ranging in age from 19 to 29 y and suffering from either tibial or fifth metatarsal injuries. However, our management of ESWT was different; the shockwave device was electromagnetic and no anesthesia was used. Moreover, the fractures were treated using a low-middle energy (0.09–0.17 mJ/mm^2) and a higher number of shock waves (4000 impulses) during each of the applications (three for the metatarsus and four for the tibia).

One and a half to three months after ESWT, the patients reported an absence of pain both at rest and when walking and radiographic evaluation showed union in all cases. The patients were free of pain 3 mo after treatment and we recommended a gradual return to the sports activity and a progressive increase in the intensity of exercise. We concluded that our results were similar to those recorded by Taki et al (2007), even though the ESWT management differed. First, the application of low-middle energy in the treatment of stress fractures was successful because it opposes the loss of balance between osteoblasts and osteoclasts, which is involved in the pathogenesis of stress fractures (Herrmann et al. 2007). Second, the use of the electromagnetic device would better stimulate proliferation and the activity of osteoblasts in bone deposition (Martini et al. 2006).

Stress fractures are a common source of pain and dysfunction in an active population; conservative treatment may well prove to be inadequate and result in nonunion, thereby delaying the resumption of sports activity. As a result, surgery may become necessary for the nonunion of stress fractures, perhaps causing complications that might prolong healing time for months to years. The case reports in this article demonstrate that ESWT is a successful and noninvasive therapy for the management of resistant stress fractures. Although several factors appear to contribute to the development of stress

Table 1. Clinical data and results after ESWT

Patient No	Mo	Side	Therapy	Age (y)	Sex	ESWT	Resolution (wk)
1	4	5th MT left	Cast	29	M	3	6
2	4	5th MT right	Cast	26	M	3	8
3	8	5th MT left	Cast	25	M	3 × 2	14
4	3	5th MT right	Cast	20	M	3	6
5	8	5th MT right	Cast+ fixation	28	M	3	6
6	3	5th MT right	Cast	27	M	3	8
7	10	Tibia right	Rest	24	M	4	6
8	4	Tibia left	Rest	22	M	4	8
9	6	Tibia right	Rest	26	M	4	8
10	5	Tibia right	Rest	19	M	4	7

ESWT = extracorporeal shock wave therapy; MT = metatarsus.

fractures, they generally occur as a result of a repetitive use injury that exceeds the intrinsic ability of the bone to repair itself. Our choice of a lower energy of ESWT in the treatment of stress fractures can be based on the rationale that ultrasound induces nitric oxide (NO) liberation at low energy, ever if the duration of NO liberation might be short after shock wave application (Altland et al. 2004). There is a link between NO and osteogenesis via the 7-d expression of the core binding factors cbfa1 (Zaragoza et al. 2006). Consequently, our application of the lower energy shock wave stimulates bone growth by nitric oxide production. The question why low intensity pulsed ultrasound did not promote fracture healing has yet to be explained. We propose to examine this question thoroughly by future clinical and biologic studies.

ESWT is a noninvasive and effective method of treatment for stress fractures that requires further studies to determine the best doses of energy, number of impulses and duration of shock wave administration. This study showed promising results using lower energy shock waves, which require no anesthesia during operation and no surgical internal fixation. This article broadens the list of clinical applications of extracorporeal shock waves by adding stress fractures, which are frequent in athletes that need to return to sports activities quickly and with good results within a relatively short time. Prospective, randomized double-blind clinical studies on nonunion and fracture healing treated by ESWT need to be conducted to extend the knowledge about the ESWT and improve its therapeutic applications.

REFERENCES

Aicher A, Heeschen C, Sasaki K, Urbich C, Zeiher AM, Dimmeler S. Low-energy shock wave for enhancing recruitment of endothelial progenitor cells: A new modality to increase efficacy of cell therapy in chronic hind limb ischemia. Circulation 2006;14:2823–2830.

Apfel RE. Acoustic cavitation: A possible consequence of biomedical uses of ultrasound. Br J Cancer Suppl 1982;5:140–146.

Altland OD, Dalecki D, Suchkova VN, Francis CW. Low-intensity ultrasound increases endothelial cell nitric oxide synthase activity and nitric oxide synthesis. J Thromb Haemost 2004;2:637–643.

Bara T, Synder M, Studniarek M. The application of shock waves in the treatment of delayed bone union and pseudoarthrosis in long bones. Ortop Traumatol Rehabil 2000;2:54–57.

Bara T, Synder M. Nine-years experience with the use of shock waves for treatment of bone union disturbances. Ortop Traumatol Rehabil 2007;9:254–258.

Bulut O, Eroglu M, Ozturk H, Tezeren G, Bulut S, Koptagel E. Extracorporeal shock wave treatment for defective nonunion of the radius: A rabbit model. J Orthop Surg (Hong Kong) 2006;14:133–137.

Benazzo F, Mosconi M, Beccarisi G, Galli U. Use of capacitive electric fields in stress fracture in athletes. Clin Orthop Rel Res 1995;310: 145–149.

Bennell KL, Brukner PD. Epidemiology and site specificity of stress fractures. Clin Sports Med 1997;16:179–196.

Boden BP, Osbahr DC, Jimenez C. Low-risk stress fractures. Am J Sports Med 2001;29:100–111.

Borsalino G, Bagnacani M, Bettati E, Fornaciari F, Rocchi R, Uluhogian S, Ceccherelli G, Cadossi R, Traina GC. Electrical stimulation of human femoral intertrochanteric osteotomies: Double blind study. Clin Orthop 1988;237:256–263.

Breithaupt MD. To the pathology of the human foot. Med Zeitung 1855; 24:169.

Chang PS, Harris RM. Intramedullary nailing for chronic tibial stress fractures. A review of five cases. Am J Sports Med 1996;24:688–692.

Chen YJ, Wurtz T, Wang CJ, Kuo YR, Yang KD, Huang HC, Wang FS. Recruitment of mesenchymal stem cells and expression of TGF-beta 1 and VEGF in the early stage of shock wave-promoted bone regeneration of segmental defect in rats. J Orthop Res 2004;22:526–534.

Ciampa AR, de Prati AC, Amelio E, Cavalieri E, Persichini T, Colasanti M, Musci G, Marlinghaus E, Suzuki H, Mariotto S. Nitric oxide mediates anti-inflammatory action of extracorporeal shock waves. FEBS Letters 2005;579:6839–6845.

DeLee JC, Evans JP, Julian J. Stress fracture of the fifth metatarsal. Am J Sports Med 1983;11:349–353.

Devas MB. Stress fractures of the tibia in athletes of "shin soreness. J Bone Joint Surg (Br) 1958;40:227–239.

Haupt G. Use of extracorporeal shock waves in the treatment of pseudoarthrosis, thendinopathy and other orthopaedic diseases. J Urol 1997;158:4–11.

Haupt G, Haupt A, Ekkernkamp A, Gerety B, Chvapil M. Influence of shock waves on fracture healing Urology 1992;39:529–532.

Herrmann M, Müller M, Scharhag J, Sand-Hill M, Kindermann W, Herrmann W. The effect of endurance exercise-induced lact acidosis on biochemical markers of bone turnover. Clin Chem Lab Med 2007; 45:1381–1389.

Johannes EJ, Kaulesar Sukul DM, Matura E. High-energy shock waves for the treatment of nonunions: an experiment on dogs. J Surg Res 1994;57:246–252.

Johnson AW, Weiss CB Jr, Wheeler DL. Stress fractures of the femoral shaft in athletes–more common than expected. A new clinical test. Am J Sports Med 1994;22:248–256.

Maisonhaute E, Prado C, White PC, Compton RG. Surface acoustic cavitation understood via nanosecond electrochemistry. Part III: Shear stress in ultrasonic cleaning. Ultrason Sonochem 2002;9:297–303.

Maitra RS, Johnson DL. Stress fractures. Clinical history and physical examination. Clin Sports Med 1997;16:259–274.

Martini L, Giavaresi G, Fini M, Borsari V, Torricelli P, Giardino R. Early effects of extracorporeal shock wave treatment on osteoblast-like cells: A comparative study between electromagnetic and electrohydraulic devices. J Trauma 2006;61:1198–1206.

Martini L, Giavaresi G, Fini M, Torricelli P, de Pretto M, Schaden W, Giardino R. Effect of extracorporeal shock wave therapy on osteoblastlike cells. Clin Orthop Relat Res 2003;269–280.

Matherson GO, Clement DB, McKenze DC, Taunton JE, Lloyd-Smith DR, MacIntyre JG. Stress fractures in athletes: A study of 320 cases. Am J Sports Med 1987;15:46–58.

Narasaki K, Shimizu H, Beppu M, Aoki H, Takagi M, Takashi M. Effect of extracorporeal shock waves on callus formation during bone lengthening. J Orthop Sci 2003;8:474–481.

Noble B. Microdamage and apoptosis. Eur J Morphol 2005;42:91–98.

Raasch WG, Hergan DJ. Treatment of stress fractures: the fundamentals. Clin Sports Med 2006;25:29–36.

Rue JH, Armstrong DW. Frassica FJ Deafenbaugh M, Wilckens JH. The effect of pulsed ultrasound in the treatment of tibial stress fractures. Orthopedics 2004;27:1192–1195.

Retting AC, Shelbourne KD. McCarroll JK Bisesi M, Watts J. The natural history and treatment of delayed union stress fractures of the anterior cortex of the tibia. Am J Sports Med 1988;16:250–255.

Schaden W, Fischer A, Sailler A. Extracorporeal shock wave therapy of nonunion or delayed osseous union. Clin Orthop Relat Res 2001;90–94.

Sharrard WJW. A double-blind trial of pulsed electromagnetic fields for delayed union of tibial fractures. J Bone Joint Surg Br 1990;72: 347–355.

Scott G, King JB. A prospective double blind trial of electrical capacitive coupling in the treatment of nonunion of long bones. J Bone Joint Surg Am 1994;76:820–826.

Taki M, Iwata O, Spiono M, Kimura M, Takagishi K. Extracorporeal shock wave therapy for resistant stress fracture in athletes. A report of five cases. Am J Sports Med 2007;35:1188–1992.

Valchanou VD, Michailov P. High energy shock waves in the treatment of delayed and nonunion of fractures. Int Orthop 1991;15:181–184.

Varner KE, Younas SA, Lintner DM, Marymont JV. Chronic anterior midtibial stress fractures in athletes treated with reamed intramedullary nailing. Am J Sports Med 2005;33:1071–1076.

Wang C-J. An Overview of shock wave therapy in musculoskeletal disorders. Chang Gung Med J 2003;26:220–232.

Warden SJ, Burr DB, Brukner PD. Stress fractures: pathophysiology, epidemiology, and risk factors. Curr Osteoporos Rep 2006;4: 103–109.

Young AJ, McAllister DR. Evaluation and treatment of tibial stress fracture. Clin Sports Med 2006;25:117–128.

Zaragoza C, López-Rivera E, García-Rama C, Saura M, Martínez-Ruíz A, Lizarbe TR, Martín-de-Lara F, Lamas S. Cbfa-1 mediates nitric oxide regulation of MMP-13 in osteoblasts. J Cell Sci 2006; 119:1896–1902.