

Extracorporeal Shock Wave Therapy Enhances Early Tendon-Bone Healing and Reduces Bone Tunnel Enlargement in Hamstring Autograft Anterior Cruciate Ligament Reconstruction

Ching-Jen Wang,* MD, Lin-Hsiu Weng,* MD, Wen-Yi Chou,* MD, San-Ling Hsu,* MD, Jih-Yang Ko,* MD, Sheung-Fat Ko,[†] MD, and Chung-Cheng Huang,^{†‡} MD

Investigation performed at Kaohsiung Chang Gung Memorial Hospital/Chang Gung University College of Medicine, Taiwan

Background: The tendon-bone healing in anterior cruciate ligament reconstruction remains controversial. Extracorporeal shock wave therapy (ESWT) has been shown to enhance tendon-bone healing in rabbits.

Hypothesis: Extracorporeal shock wave therapy may improve the tendon-bone healing in hamstring autograft anterior cruciate ligament reconstruction in humans.

Study Design: Cohort study; Level of evidence, 2.

Methods: Thirty-four patients (34 knees) were randomized into ESWT and control groups with 17 patients (17 knees) in each group. The ESWT group underwent single-bundle anterior cruciate ligament reconstruction and received ESWT to the midtibia tunnel after surgery. The control group received anterior cruciate ligament surgery without ESWT. The evaluations included Lysholm score, International Knee Documentation Committee (IKDC) score, KT-1000 arthrometer testing, radiographs, bone mineral density, and magnetic resonance imaging.

Results: The ESWT group showed significantly better Lysholm scores than did the control group at 1 year (96.67 ± 2.58 vs 86.71 ± 10.58 ; $P = .043$) and 2 years (97.92 ± 2.43 vs 89.27 ± 8.09 ; $P < .001$) postoperatively. No significant differences were noted in the IKDC scores between the ESWT and control groups at 1 year (58.64 ± 6.38 vs 53.31 ± 10.57) and 2 years (63.78 ± 5.74 vs 58.0 ± 9.36) postoperatively (both $P > .05$). The KT-1000 arthrometer values of anterior-posterior laxity of the knee in the ESWT group were significantly better than those of the control group only at 2 years postoperatively (2.40 ± 0.91 vs 3.47 ± 1.25 ; $P = .041$). The size of the middle third tibial tunnel on radiographs was significantly smaller in the ESWT group at 2 years after treatment ($P = .016$). No discernable difference was noted in bony appearance and bone mineral density values between the 2 groups. On magnetic resonance imaging, the ESWT group showed significantly better integration of tendon graft to bone marrow and lesser tibial tunnel enlargement as compared with the control group (all $P < .05$).

Conclusion: Application of ESWT to the bone tunnel significantly enhanced the early tendon-bone healing and decreased the tibial tunnel enlargement after anterior cruciate ligament reconstruction in the short term.

Keywords: ACL; shock wave; tendon-bone healing

[‡]Address correspondence to Chung-Cheng Huang, MD, Department of Diagnostic Radiology, Chang Gung Memorial Hospital/Kaohsiung Medical Center, 123 Ta-Pei Road, Niao Sung Hsiang, Kaohsiung, Taiwan 833 (e-mail: w281211@adm.cgmh.org.tw).

*Department of Orthopedic Surgery, Chang Gung University College of Medicine, Chang Gung Memorial Hospital/Kaohsiung Medical Center, Kaohsiung, Taiwan.

[†]Department of Diagnostic Radiology, Chang Gung University College of Medicine, Chang Gung Memorial Hospital/Kaohsiung Medical Center, Kaohsiung, Taiwan.

One or more authors has declared the following potential conflict of interest or source of funding: Dr Wang served as a member of the scientific committee of Sanuwave until November 2010.

Anterior cruciate ligament (ACL) reconstruction is usually performed by the transfer of a free tendon autograft into a bone tunnel. The success of ligament reconstruction relies on the firm healing of tendon to bone in the bone tunnel.³⁶ The phenomenon of ligamentization after free autograft ACL reconstruction remains controversial. Previous studies showed conflicting results.^{2-4,7,11,16,26,35} Some studies demonstrated the phenomenon of ligamentization after implantation of tendon autograft into a bone tunnel.^{2,7,16,26,35} However, other studies showed the opposite results and concluded that metaphyseal bone and tendon do not heal together.^{3,4,11}

Many factors may influence the healing of tendon to bone. Some studies demonstrated that bone morphogenetic

protein (BMP) is effective in promoting bone formation and the healing of tendon to bone in a bone tunnel.^{10,19,25,27} Other studies attempted to improve the healing of tendon to bone with different therapeutic modalities including application of periosteum augmentation, calcium-phosphate cement, tricalcium phosphate, calcium phosphate–hybridized tendon, granulocyte colony-stimulating factor, magnesium-based adhesive, hyperbaric oxygen therapy, and gene transfer.⁸ Some reported limited success, but none showed universal results. Many other studies showed that physical factors such as continuous passive motion (CPM) and extracorporeal shock wave therapy (ESWT) can enhance the healing of periosteal and free tendon autografts to bone.^{23,31–33} Based on histomorphologic examination and biomechanical testing, our previous study demonstrated that ESWT is effective in promoting tendon–bone healing in a bone tunnel after ACL reconstruction in a rabbit model.³³ In a clinical setting, bone tunnel enlargement on radiographs and MRI is often used as an evaluation parameter after ACL reconstruction.¹⁵ The implication of bone tunnel enlargement after ACL reconstruction and subsequent mechanical instability is still debated.^{5,8,13,15,20,29} Some authors concluded that bone tunnel enlargement is the main contributory factor that leads to laxity of the ACL autograft.^{15,20,29} Nevertheless, only a few studies have addressed effective methods to prevent or reduce the risk of bone tunnel enlargement after ACL reconstruction.²⁴ We hypothesized that ESWT may be effective in promoting tendon–bone healing in a bone tunnel after ACL reconstruction with improved integration of the autograft to bone and a reduction in bone tunnel enlargement in humans. The purpose of this prospective study was to evaluate the effectiveness of ESWT on tendon–bone healing and the reduction in tibial tunnel enlargement after hamstring autograft ACL reconstruction.

MATERIALS AND METHODS

The Institutional Review Board approved this study. Each patient signed an informed consent before participation in the study. Thirty-four patients (34 knees) were included in the study. Patients were randomly divided into 2 groups using computer-generated block labels. Seventeen patients (17 knees) with odd numbers were assigned to the ESWT group, whereas 17 patients (17 knees) with even numbers were assigned to the control group. The flowchart of patient recruitment is shown in Figure 1. The demographic characteristics are shown in Table 1. Patients in the ESWT group underwent arthroscopic single-bundle ACL reconstruction using semitendinosus and gracilis tendon autografts and received ESWT after surgery. Patients in the control group received ACL surgery, but no ESWT.

Anterior Cruciate Ligament Reconstruction

With the patient under general anesthesia, the affected leg was draped in sterile fashion. A complete arthroscopic

TABLE 1
Demographic Characteristics of the Patients^a

	ESWT Group (N = 17)	Control Group (N = 17)	P
Age, y ^b	28.3 ± 8.1 (15-45)	29.6 ± 8.2 (18-53)	.636
Males/females	14/3	14/3	1.000
Right knee/left knee	11/6	8/9	.300
Duration of symptoms, mo ^b	11.4 ± 10.9 (1-36)	10 ± 11.9 (1-48)	.534
Mechanism of injury, No.			
Baseball injury	5	11	.213
Traffic accident	5	3	.524
Falling accident	5	0	.035
Other	2	3	.676
Length of follow-up, mo ^b	25.76 ± 1.83 (24~30)	26.47 ± 2.03 (24~30)	.290

^aThe numeric data between the extracorporeal shock wave therapy (ESWT) and control groups are analyzed with Mann-Whitney *U* tests and the nominal data are analyzed with χ^2 or Fisher exact tests.

^bMean ± standard deviation (range).

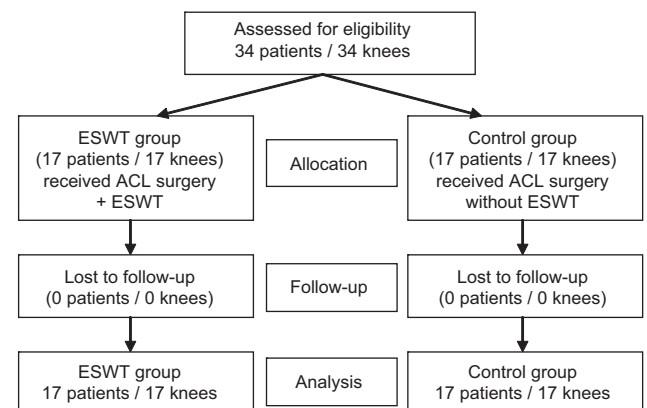


Figure 1. Flowchart of patient recruitment. ACL, anterior cruciate ligament; ESWT, extracorporeal shock wave therapy.

examination of the knee was performed. The associated injuries including meniscal tears and chondral lesions were identified. Meniscal tears were noted in 8 of the knees in the ESWT group and 9 in the control group. Chondral defects were seen in 2 cases in each group. The concomitant surgeries for meniscal tears and chondral defects were performed before ACL surgery. During ACL reconstruction, the ACL stump was partially debrided. The locations of the femoral tunnel on the lateral femoral condyle and the tibial tunnel in the tibia eminence were verified anatomically using the ACL footprints as the landmarks under arthroscopy. A 25-mm–long incision was made on the anteromedial aspect of the proximal tibia. The semitendinosus and gracilis tendons were harvested with a tendon stripper. The autografts were tripled or quadrupled and sutured into a graft bundle. The average autograft size was 8 mm in diameter and 85 mm in length. The autograft was

⁸References 6, 9, 12, 17, 18, 22, 28, 30, 37, 38.

pretensioned with 15 lb for 15 minutes before implantation. Acufex instruments (Smith & Nephew, Andover, Massachusetts) were used in ACL reconstruction. The guide pins were inserted to the desired locations, and the femoral and tibial tunnels were created with a graft size-matched reamer. The femoral tunnel was drilled through an arthroscopic portal and reamed to a depth of 23 mm. The tendon graft was delivered from the tibial tunnel into the knee joint and then the femoral tunnel. Both ends of the grafts were secured with bioscrews (Mitek products, Ethicon Inc, a Johnson & Johnson Company, Marlborough, Massachusetts) with the knee at 20° to 30° of flexion. The bioscrews were either the same size or 1 size smaller than the bone tunnel depending on the bone quality.

Extracorporeal Shock Wave Therapy Application

Patients in the ESWT group also received ESWT immediately after ACL surgery under the same anesthesia. The source of shock wave was from an Ossatron (High Medical Technology, Lengwil, Switzerland; now SANUWAVE, Alpharetta, Georgia). The surgical wounds were covered with a sterile cellulose barrier, and ultrasound gel was applied to the skin in contact with the shock wave tube. The shock wave was focused at the middle third of the tibial tunnel, and the depth of treatment was verified by raising the height of the table until the 2 ring markers of the device synchronized on C-arm imaging (Figure 2). Application of 1500 impulses of ESWT at 20 kV (equivalent to 0.30 mJ/mm² energy flux density) was administered to the middle third of the tibial tunnel in a single session. The dosage chosen in this study was based on our previous experience.³⁴ For study purposes, ESWT was applied only to the tibial tunnel. Immediately after ESWT application, the local area was checked for swelling, ecchymosis, hematoma, etc. Patients in the control group received no ESWT after ACL reconstruction.

Postoperatively, all patients received the same rehabilitation program that included crutch-walking with partial weightbearing, range of knee motion, and quadriceps and hamstring exercises for 3 to 6 weeks. Patients were discharged when they were capable of independent crutch-walking and continued outpatient physical therapy. Full weightbearing was permitted after 6 weeks.

Clinical Assessment and Image Study

Follow-up examinations were scheduled at 1, 3, 6, 12, and 24 months and then yearly after surgery. The evaluations included clinical assessment, radiographs, bone mineral density (BMD), and MRI of the affected knee. Clinical assessments including Lysholm functional score, International Knee Documentation Committee (IKDC) subjective score, and anterior-posterior (A-P) laxity of the knee were performed before treatment and at each follow-up visit. The A-P knee laxity was evaluated with physical examination and KT-1000 arthrometer (MEDmetric, San Diego, California) at 20 lb of pull. Radiographs of the knee in anteroposterior and lateral views were obtained 1 week after



Figure 2. The C-arm imaging of the proximal tibia in lateral projection shows the depth of extracorporeal shock wave therapy application.

treatment and at each follow-up visit. Radiographs were used to evaluate the bony appearance and the changes of the tibial tunnel size at the proximal third, middle third, and distal third on anteroposterior view. Bone mineral density in the region of interest around the tibial tunnel was performed at 1 week (T0), 6 months (T6m), and 24 months (T24m) after treatment using DEXA (dual energy x-ray absorptiometry). The BMD was used to assess the changes in bone density of the proximal tibia.

An MRI scan of the knee was also performed at T0, T6m and T24m after treatment. The imaging study was carried out using a 3.0-T MRI system (Signa Excite HD, GE Healthcare, Milwaukee, Wisconsin). Cyst formation or fluid collection in or around the tibial tunnel, if any, was documented. The baseline MRI protocol included proton-weighted coronal and sagittal, proton-weighted oblique coronal and oblique sagittal along the tibial tunnel axis, and T1-weighted oblique axial and fat-saturated proton-weighted oblique axial perpendicular to the long axis of tibial tunnel pulse sequences. The signal change of autograft, autograft-bone marrow integration, diameter, and area of the tibial tunnel on MRI were recorded. The oblique axial fat-suppressed proton-weighted images were employed to assess the autograft cross-sectional areas and autograft-bone integration (Figure 3A). The upper, middle, and lower third tibial tunnel images were captured using the PACS



Figure 3. Magnetic resonance imaging of a 31-year-old male patient in the ESWT group. A, the fat-suppressed oblique axial proton-weighted image exhibits hypointense autograft (arrow) and screw (open arrow) in the upper third of the tibial tunnel immediately after surgery. Also noted is the edematous change of subcutis and Hoffa fat pad. B, 6 months after extracorporeal shock wave therapy, integration of the autograft with surrounding bone marrow of the tibial tunnel (open arrowhead) is evident. The best-fit circle of the screw is used for area calculations.

(picture archiving and communication system) and then analyzed with Image-Pro Plus software (Media Cybernetics, Silver Spring, Maryland).^{8,29} The color threshold level within the software program was set to encompass the low-signal tendon autograft in the tibial tunnel for calculating autograft area. The corresponding screw area in the tibial tunnel was measured digitally using a computer-generated best-fit circle (Figure 3B).^{8,14,21,29} To minimize measurement error attributable to variance of the corresponding cross-sectional areas taken by sequential MRI examinations, we used the autograft–screw area ratio (ASR, which is the autograft area over screw area) to represent the cross-sectional area of the autograft. The ratios of ASR at T6m (ASRT6) divided by ASR at T0 (ASRT0), ASR at T24m (ASRT24) divided by ASRT0, and ASRT24 divided by ASRT6 were measured to represent the ratios of decreasing low-signal autograft between each 2 time sets. The integration of autograft was defined as loss of low-signal autograft attributable to incorporation of the graft into the surrounding bone marrow on MRI. Therefore, the integration ratio of the autograft at T6m or T24m could be obtained from the following formulas: integration ratio at T6m = $1 - (\text{ASRT6}/\text{ASRT0})$, at T24m = $1 - (\text{ASRT24}/\text{ASRT0})$, and at T6m to T24m = $1 - (\text{ASRT24}/\text{ASRT6})$. The integration ratios of the upper, middle, and lower third of the tibial tunnel were measured separately and the mean of these 3 integration ratios was used to evaluate the effectiveness of ESWT on tendon–bone healing.

The A-P and medial-lateral (M-L) diameters of the upper, middle, and lower third of the tibial tunnel were recorded using the oblique axial T1-weighted images (Figure 4). The corresponding area of the tibial tunnel was calculated using the area of ellipse as $\pi \times \text{half A-P diameter} \times \text{half M-L diameter}$. The enlargement ratios of A-P diameter, M-L diameter, and area of the tibial tunnel were measured by the values at T6m/values at T0, values at T24m/values at T0, and values at T24m/values at T6m. The mean enlargement ratio of the upper, middle, and lower third of the tibial tunnel was employed to analyze tunnel enlargement. Two radiologists blinded to the study design jointly performed the MRI interpretation.

Statistical Analysis

A sample size of 17 per group would be required to detect a minimal clinically important difference of 1.2 and variance of 0.75 in the autograft screw ratio measured at 6 months after treatment between treatment and control groups with $\alpha = .05$ and power = .80. The data before treatment and at different time intervals after treatment within the same group were compared statistically using a Wilcoxon signed-rank test. The nominal and numeric data between the ESWT group and the control group were compared statistically with χ^2 or Fisher exact test and Mann-Whitney *U* test, respectively. The statistical significance was set at $P < .05$.

TABLE 2
Lysholm Functional Score, IKDC Subjective Score, and KT-1000 Arthrometer for Anterior-Posterior Laxity of the Knee^a

Evaluation (N = 17)	Before Treatment	At 1 Year	At 2 Years	P ¹	P ²	P ³
Lysholm score						
ESWT group	42.65 ± 10.76 (28-59)	96.67 ± 2.58 (94-99)	97.92 ± 2.43 (95-100)	.027	.003	.272
Control group	42.53 ± 13.55 (21-63)	86.71 ± 10.58 (66-99)	89.27 ± 8.09 (66-100)	.017	.001	.055
P ⁴	.959	.043	<.001			
IKDC score						
ESWT group	23.43 ± 8.64 (6.3-37.3)	58.64 ± 6.38 (51.3-68.3)	63.78 ± 5.74 (58.3-71.3)	.027	.001	.181
Control group	19.13 ± 8.83 (2.3-33.3)	53.31 ± 10.57 (32.3-64.3)	58.0 ± 9.36 (32.3-71.3)	.018	.001	.091
P ⁴	.087	.528	.054			
KT-1000, mm						
ESWT group	9.90 ± 1.82 (8.33-12.26)	3.28 ± 0.54 (0-1.00)	2.40 ± 0.91 (1-4)	.028	.003	.052
Control group	9.83 ± 0.72 (9.2-11.2)	3.50 ± 0.52 (1.0-2.28)	3.47 ± 1.25 (1-6)	.017	.005	.584
P ⁴	.664	.126	.041			

^aThe data are shown as mean ± standard deviation (range). The data are analyzed with Wilcoxon signed-rank tests within the same group and Mann-Whitney *U* tests between 2 groups. ESWT, extracorporeal shock wave therapy; IKDC, International Knee Documentation Committee; P¹, comparison of data before treatment and at 1 year after treatment; P², comparison of data before treatment and at 2 years after treatment; P³, comparison of data at 1 year and at 2 years after treatment; P⁴, comparison of ESWT group with control group before and after treatment.

TABLE 3
Tibial Tunnel Size on Radiographs and BMD Around Tibial Tunnel^a

Tibial Tunnel, mm (N = 17)	At T0	At T12m	At T24m	P ¹	P ²	P ³
ESWT group						
Proximal third	11.16 ± 1.25 (9.3-12.8)	11.97 ± 1.24 (9.46-13.74)	11.22 ± 1.39 (8.45-13.13)	.069	.441	.183
Middle third	11.0 ± 1.75 (8.58-13.75)	11.77 ± 1.49 (8.7-13.5)	8.80 ± 0.91 (7.12-10.28)	.161	.033	.015
Distal third	10.18 ± 2.01 (6.8-14.4)	10.76 ± 1.74 (7.89-13.03)	8.92 ± 0.76 (7.81-10.07)	.407	.062	.061
Control group						
Proximal third	10.45 ± 1.76 (8.59-14.78)	11.64 ± 1.82 (9.1-15.18)	11.03 ± 1.6 (10.43-13.07)	.008	.646	.161
P ⁴⁻¹	.128	.393	.914			
Middle third	10.33 ± 1.6 (8.92-13.88)	11.16 ± 1.54 (9.58-14.08)	10.48 ± 1.37 (9.71-12.35)	.06	.799	.086
P ⁴⁻²	.478	.529	.016			
Distal third	9.52 ± 0.85 (8.49-11.12)	10.79 ± 1.07 (9.51-12.25)	9.54 ± 1.40 (7.35-12.52)	.09	.066	.114
P ⁴⁻³	.713	.796	.115			
BMD, g/cm ²						
	At T0	At T6m	At T24m			
ESWT group	0.83 ± 0.21 (0.56-1.31)	0.8 ± 0.07 (0.71-0.9)	0.86 ± 0.17 (0.60-1.22)	.686	.363	.393
Control group	0.89 ± 0.15 (0.72-1.24)	0.8 ± 0.13 (0.59-0.93)	0.81 ± 0.2 (0.19-1.03)	.916	.345	.701
P ⁴⁻⁴	.266	.686	.984			

^aThe data are presented as mean ± standard deviation (range). BMD, bone mineral density; ESWT, extracorporeal shock wave therapy; T0, T6m, T12m, and T24m: 1 week, 6 months, 12 months, and 24 months after treatment, respectively; P¹, comparison of tibial tunnel size on radiograph at T12m and T0, and BMD at T6m and T0; P², comparison of tibial tunnel size on radiograph and BMD at T24m and T0; P³, comparison of tibial tunnel size on radiograph at T24m and T12m, and BMD at T24m and T6m; P⁴⁻¹, P⁴⁻², and P⁴⁻³: comparison of the ESWT group with control group in proximal third, middle third, and distal third, respectively; P⁴⁻⁴, comparison of ESWT group with control group in BMD.

P¹, P², and P³ are by Wilcoxon signed-rank tests; P⁴⁻¹, P⁴⁻², P⁴⁻³, and P⁴⁻⁴, by Mann-Whitney *U* tests.

RESULTS

Except for a falling accident injury, there were no significant differences in the remaining data of the demographic characteristics in the patients between the 2 groups (Table 1). The Lysholm functional score, IKDC subjective score, and KT-1000 arthrometer for A-P laxity of the knee are summarized in Table 2. Compared with the data before treatment, significant improvements in functional score, IKDC subjective score, and A-P laxity of the

knee were noted in both groups at 1 and 2 years after treatment (all *P* < .05). However, the ESWT group showed significantly better Lysholm functional score and A-P laxity of the knee as compared with the control group at 2 years (all *P* < .05) but the IKDC subjective score was not different between the 2 groups (*P* = .054). The tibial tunnel size on radiographs and BMD values at T0, T6m, T12m, and T24m are shown in Table 3. The size of the tibial tunnel showed a trend of increase at T12m, and a decrease at T24m in both groups. Nevertheless, the size at the middle

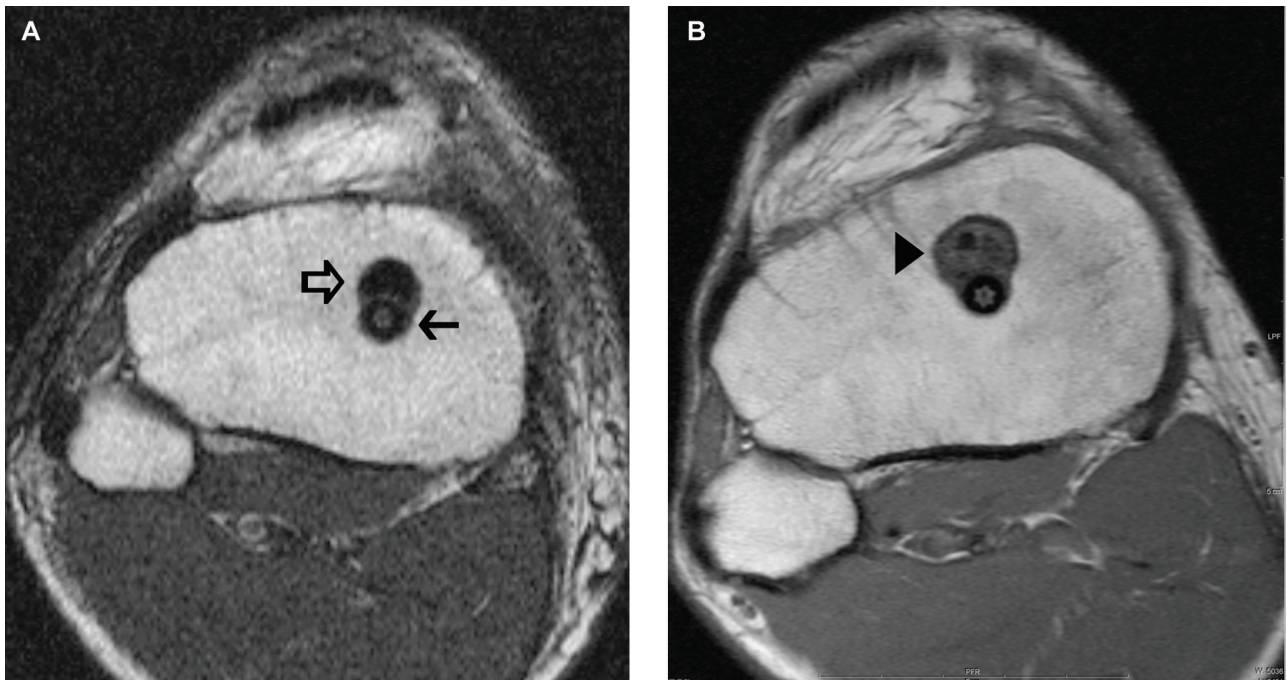


Figure 4. Magnetic resonance imaging of a 27-year-old male patient in the control group. A, oblique axial T1-weighted axial image depicts anterior cruciate ligament autograft (open arrow) and screw (arrow) in the tibial tunnel immediately after surgery. B, apparent enlargement of the tibial tunnel (arrowhead) is noted 2 months later.

third of the tibial tunnel was significantly smaller in the ESWT group as compared with the control group ($P = .016$), suggesting that the changes in tibial tunnel size were more pronounced at the middle third, where ESWT was applied. The changes in BMD values and the bony appearance of the proximal tibia revealed no discernible difference between the 2 groups (all $P > .05$).

On MRI, the autograft appeared homogeneous and hypointense in the tibial tunnel at T0 that was similar to the signal characteristics of the native harvest tissue (Figure 4A). Partial loss of hypointense autograft appearance and gradual integration into the surrounding bone marrow of the tibial tunnel were observed at T6m and T24m in both groups. The mean ASRs and integration ratios of the ACL autografts in the tibial tunnel at T0, T6m, and T24m are summarized in Table 4. Overall, gradual reduction of the autograft area with time was noted in both groups. The mean ASRs in the ESWT group at T6m and T24m were significantly smaller than those in the control group ($P = .005$ and $< .001$, respectively). Compared with the autograft at T0, the mean integration ratios at T6m and T24m in the ESWT group were significantly better than those in the control group (both $P < .001$). However, no significant difference was demonstrated on the data between T24m and T6m in both groups. The enlargement ratios of diameters and areas of the tibial tunnel on MRI are also listed in Table 4. Compared with the values at T0, all enlargement ratios at T6m and T24m in A-P diameters, M-L diameters, and areas in the ESWT group were significantly lower than those in the control group (all $P < .05$). Nonetheless, only the enlargement ratio of the area in ESWT group at

T24m/T6m appeared significantly lower than that in the control group ($P = .029$). Cyst formation or fluid collection in or around the tibial tunnel was not noticed in either group.

Complications

There were no systemic or local complications or ESWT device–related problems. There were no infections or neurovascular complications in this series.

DISCUSSION

The healing of tendon to bone in a bone tunnel continues to be debated.^{2,4,36} Many studies attempted to improve the healing between tendon and bone with different materials and methods. Some achieved limited success, but none showed any universal results.⁸ The results of the current study demonstrated that application of ESWT significantly improved the tendon–bone healing in the tibial bone tunnel as shown on MRI at 6 and 24 months as compared with the control group without ESWT. Some authors reported that autograft ligamentization in the bone tunnel after ACL reconstruction was ascribed to ensuing vascularization of perigraft soft tissue with subsequent synovialization and remodeling.^{1,14} We have previously shown that ESWT induces the ingrowth of neovascularization with upregulation of angiogenic growth factors and improves blood perfusion and tissue regeneration.^{31,32} It is reasonable to believe that ESWT accelerates the tendon–bone healing via the

TABLE 4

Mean Autograft Screw Ratios, Autograft Integration Ratios, and Enlargement Ratios of Diameters and Areas of the Tibial Tunnels on MRI for the Patients in ESWT and Control Groups^a

	ESWT Group (N = 17), Mean ± SD	Control Group (N = 17), Mean ± SD	P ^b
Autograft screw ratio			
T0	4.0 ± 1.4	4.1 ± 1.2	.483
T6m	1.1 ± 0.8	2.0 ± 0.7	.005
T24m	0.5 ± 0.3	1.0 ± 0.3	<.001
Autograft integration ratio			
T6m/T0	0.73 ± 0.16	0.50 ± 0.17	<.001
T24m/T0	0.88 ± 0.05	0.76 ± 0.09	<.001
T24m/T6m	0.48 ± 0.20	0.44 ± 0.18	.357
Tibial tunnel enlargement ratio			
AP-diameter			
T6m/T0	1.11 ± 0.11	1.24 ± 0.11	.004
T24m/T0	1.10 ± 0.28	1.38 ± 0.39	.014
T24m/T6m	0.98 ± 0.19	1.02 ± 0.15	.905
M-L diameter			
T6m/T0	1.07 ± 0.09	1.17 ± 0.12	.016
T24m/T0	0.95 ± 0.13	1.14 ± 0.15	.001
T24m/T6m	0.88 ± 0.10	0.96 ± 0.06	.014
Area			
T6m/T0	1.20 ± 0.19	1.45 ± 0.23	.002
T24m/T0	1.04 ± 0.33	1.57 ± 0.41	.001
T24m/T6m	0.87 ± 0.27	0.97 ± 0.13	.029

^aESWT, extracorporeal shock wave therapy; SD, standard deviation; T0, T6m, and T24m: 1 week, 6 months, and 24 months after treatment; autograft screw ratio = mean autograft cross-sectional area/screw cross-sectional area; integration ratio = 1 - (autograft screw ratio at T6m or T24m/autograft area ratio at T0 or T6m); A-P, anterior-posterior; M-L, medial-lateral; enlargement ratio = the value of diameter or area at T6m or T24m/value of diameter or area at T0 or T6m.

^bAll P values are analyzed by Mann-Whitney U tests.

increases of vascularity associated with elevated angiogenic and osteogenic growth factors in the bone tunnel.³¹⁻³³

Some studies reported that the maturation of the tendon-bone interface is complete from 6 to 12 months after ACL reconstruction.²¹ Before autograft maturation has taken place, it is necessary that temporary fixation of the autograft with bioscrews be undertaken for autograft protection after ACL reconstruction. Many factors may affect the outcome of ACL reconstruction, including tunnel placement and autograft tension. The results of the current study demonstrated that ESWT significantly accelerated the healing of tendon to bone as shown on MRI at 6 and 24 months, and it produced a better Lysholm functional score but not a better IKDC score after ACL reconstruction in the short term. The ESWT group is expected to show better functional outcomes as a result of better autograft integration after ESWT. However, the ultimate clinical value of ESWT in ACL reconstruction can only be ascertained with long-term follow-up results.

In the clinical setting, MRI is considered to be the best method in the evaluation of the healing of tendon to bone at the tendon-bone interface after ACL reconstruction in human subjects.^{8,13,20,24,29} The implication of bone tunnel enlargement after ACL reconstruction and subsequent mechanical instability is still debated.^{5,8,13,15,20,29} Both radiographs and MRI can be used to evaluate the bone tunnel enlargement after ACL surgery. However, MRI provides more precise information at the tendon-bone interface including the integration of the autograft; the contact, and the gap, if any, between tendon and bone; the enlargement of bone tunnel; and the overall healing of tendon to bone. The functional outcomes after ACL reconstruction should be assessed in conjunction with clinical assessment, ligament stability, radiographs, and MRI studies. Better functional outcomes are parallel to the integrity of the autograft and healing of tendon-bone as shown on MRI. In our study, the ESWT group exhibited significantly smaller middle third of the tunnel size on radiographs at 2 years, and significantly less enlargement of the tibial tunnel in A-P diameter, M-L diameter, and area of the tibial tunnel on MRI. Several reports addressed the theory that tibial tunnel enlargement might play a pivotal role in the ultimate laxity of the autograft.^{15,20,29} However, other studies reported no correlation between tibial tunnel enlargement, knee stability, joint function, and patient satisfaction scores after ACL reconstruction in the short term.^{5,8,13} In this study, the ESWT-treated knees showed a better Lysholm but not a better IKDC score and A-P laxity of the knee when compared with the controls in the short term. Furthermore, MRI exhibited significant promotion of tendon-bone healing and decrease of tibial tunnel enlargement at 6 and 24 months after ESWT. Long-term results are needed to confirm the clinical efficacy of ESWT in ACL reconstruction.

There are limitations in this study. The size of the patient population was small and that may cause low power of analysis. The follow-up time of this study was relatively short, and the functional results presented in this study may prove to be different in long-term follow-up. Furthermore, the dosage of ESWT so chosen in this study was based on our previous experience, and the optimal dosage of ESWT is yet to be determined.

CONCLUSION

Application of ESWT significantly accelerated the early tendon-bone healing and reduced the tibial tunnel enlargement on MRI after ACL surgery in the short term. The ESWT-treated knees showed a better Lysholm but not a better IKDC score and A-P laxity of the knee when compared with the controls. More studies are needed to ascertain the long-term value of ESWT on the functional outcome after ACL reconstruction.

REFERENCES

1. Amiel D, Kleiner JB, Roux RD, Harwood FL, Akeson WH. The phenomenon of "ligamentization": anterior cruciate ligament reconstruction with autogenous patellar tendon. *J Orthop Res.* 1986;4:162-172.

2. Arnoczky SP, Torzilli PA, Warren RF, Allen AA. Biologic fixation of ligament prosthesis and augmentation: an evaluation of bone ingrowth in the dog. *Am J Sports Med.* 1988;16:106-112.
3. Bosch U, Kasperczyk W, Reinert C, Oestern HJ, Tscherner H. Healing at graft fixation site under functional conditions in posterior cruciate ligament reconstruction: a morphological study in sheep. *Arch Orthop Trauma Surg.* 1989;108(3):154-158.
4. Bosch U, Kasperczyk WJ: Healing of the patellar tendon autograft after posterior cruciate ligament reconstruction – a process of ligamentization? An experimental study in a sheep model. *Am J Sports Med.* 1992;20(5):558-566.
5. Buelow JU, Siebold R, Ellermann A. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. *Knee Surg Sports Traumatol Arthrosc.* 2002;10(2):80-85.
6. Chen CH, Chen WJ, Shih CH, Yang CY, Liu SJ, Lin PY. Enveloping the tendon graft with periosteum to enhance tendon-bone healing in a bone tunnel: a biomechanical and histologic study in rabbits. *Arthroscopy.* 2003;19(3):290-296.
7. Forward AD, Cowan RJ: Tendon suture to bone: an experimental investigation in rabbits. *J Bone Joint Surg Am.* 1963;45:807-823.
8. Fules PJ, Madhav RT, Goddard RK, Newman-Sanders A, Mowbray MA. Evaluation of tibia bone tunnel enlargement using MRI scan cross-sectional area measurement after autologous hamstring tendon ACL replacement. *Knee.* 2003;10:87-91.
9. Gulotta LV, Kovacevic D, Ying L, Ehteshami JR, Montgomery S, Rodeo SA. Augmentation of tendon-to-bone healing with a magnesium-based bone adhesive. *Am J Sports Med.* 2008;36(7):1290-1297.
10. Hashimoto Y, Yoshida G, Toyoda H, Takaoka K. Generation of tendon-to-bone interface “enthesiis” with use of recombinant BMP-2 in a rabbit model. *J Orthop Res.* 2007;25(11):1415-1424.
11. Hausman M, Bain S, Ribin C. Reluctance of metaphyseal bone to heal to tendon: histologic evidence for poor mechanical strength. *Trans Orthop Res Soc.* 1989;14:277.
12. Huangfu X, Zhao J. Tendon-bone healing enhancement using injectable tricalcium phosphate in a dog anterior cruciate ligament reconstruction model. *Arthroscopy.* 2007;23(5):455-462.
13. Jansson KA, Harilainen A, Sandelin J, Karjalainen PT, Aronen HJ, Tallroth K. Bone tunnel enlargement after anterior cruciate ligament reconstruction with the hamstring autograft and endobutton fixation technique: a clinical, radiographic and magnetic resonance imaging study with 2 years follow-up. *Knee Surg Sports Traumatol Arthrosc.* 1999;7(5):290-295.
14. Jansson KA, Karjalainen PT, Harilainen A, et al. MRI of anterior cruciate ligament repair with patellar and hamstring tendon autografts. *Skeletal Radiol.* 2001;30:8-14.
15. Järvelä T, Moisala AS, Paakkala T, Paakkala A. Tunnel enlargement after double-bundle anterior cruciate ligament reconstruction: a prospective, randomized study. *Arthroscopy.* 2008;24(12):1349-1357.
16. Kernwein G, Fahey J, Garrison M. The fate of tendon, fascia and elastic connective tissue transplanted into bone. *Ann Surg.* 1938;108:285-290.
17. Kyung HS, Kim SY, Oh CW, Kim SJ. Tendon-to-bone tunnel healing in a rabbit model: the effect of periosteum augmentation at the tendon-to-bone interface. *Knee Surg Sports Traumatol Arthrosc.* 2003;11(1):9-15.
18. Lattermann C, Zelle BA, Whalen JD, et al. Gene transfer to the tendon-bone insertion site. *Knee Surg Sports Traumatol Arthrosc.* 2004;12(5):510-515.
19. Martinek V, Latterman C, Usas A, et al. Enhancement of tendon-bone integration of anterior cruciate ligament grafts with bone morphogenetic protein-2 gene transfer: a histological and biomechanical study. *J Bone Joint Surg Am.* 2002;84(7):1123-1131.
20. Moisala AS, Järvelä T, Paakkala A, Paakkala T, Kannus P, Järvinen M. Comparison of the bioabsorbable and metal screw fixation after ACL reconstruction with a hamstring autograft in MRI and clinical outcome: a prospective randomized study. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(12):1080-1086.
21. Murakami Y, Sumen Y, Ochi M, Fujimoto E, Deie M, Ikuta Y. Appearance of anterior cruciate ligament autografts in their tibial bone tunnels on oblique axial MRI. *Magn Reson Imaging.* 1999;17:679-687.
22. Mutsuzaki H, Sakane M, Nakajima H, et al. Calcium-phosphate-hybridized tendon directly promotes regeneration of tendon-bone insertion. *J Biomed Mater Res A.* 2004;70(2):319-327.
23. O'Driscoll SW, Salter RB. The induction of neochondrogenesis in free intra-articular periosteal autografts under the influence of continuous passive motion: an experimental investigation in the rabbit. *J Bone Joint Surg Am.* 1984;66:1248-1257.
24. Paessler HH, Mastrokalos DS. Anterior cruciate ligament reconstruction using semitendinosus and gracilis tendons, bone patellar tendon, or quadriceps tendon-graft with press-fit fixation without hardware: a new and innovative procedure. *Orthop Clin North Am.* 2003;34(1):49-64.
25. Reddi AH. Role of morphogenetic proteins in skeletal tissue engineering and regeneration. *Nat Biotechnol.* 1998;16:247-252.
26. Rodeo SA, Arnoczky SP, Torzilli PA, Hidaka C, Warren RF. Tendon-healing in a bone tunnel: a biomechanical and histological study in the dog. *J Bone Joint Surg Am.* 1993;75:1795-1803.
27. Rodeo SA, Suzuki K, Deng XH, Wozney J, Warren RF. Use of recombinant human bone morphogenetic protein-2 to enhance tendon healing in a bone tunnel. *Am J Sports Med.* 1999;27(4):476-488.
28. Sasaki K, Kuroda R, Ishida K, et al. Enhancement of tendon-bone osteointegration of anterior cruciate ligament grafts using granulocyte colony-stimulating factor. *Am J Sports Med.* 2008;36(8):1519-1527.
29. Singhal MC, Holzhauser M, Powell D, Johnson DL. MRI evaluation of the tibia tunnel/screw/tendon interface after ACL reconstruction using bioabsorbable interference screw. *Orthopedics.* 2008;31(6):575-579.
30. Tien YC, Chih TT, Lin JH, Ju CP, Lin SD. Augmentation of tendon-bone healing by the use of calcium-phosphate cement. *J Bone Joint Surg Br.* 2004;86(7):1072-1076.
31. Wang CJ, Huang SY, Pai CH. Shock wave enhanced neovascularization at the bone-tendon junction: a study in a dog model. *J Foot Ankle Surg.* 2002;41(1):16-22.
32. Wang CJ, Wang FS, Yang KD, et al. Shock wave therapy induces neovascularization at the tendon-bone junction: a study in rabbits. *J Orthop Res.* 2003;21:984-989.
33. Wang CJ, Wang FS, Yang KD, Weng LH, Sun YC, Ko YJ. The effect of shock wave treatment at the tendon-bone interface: a histomorphological and biomechanical study in rabbits. *J Orthop Res.* 2005;23:274-280.
34. Wang CJ, Yang KD, Wang FS, Hsu CC, Chen HH. Shock wave treatment shows dose-dependent enhancement of bone mass and bone strength after fracture of the femur. *Bone.* 2004;34:225-230.
35. Whiston TB, Walmsley R. Some observations on the reactions of bone and tendon after tunneling of bone and insertion of tendon. *J Bone Joint Surg Br.* 1960;42:377-386.
36. Woo SL, Maynard J, Butler D, et al. Ligament, tendon, and joint capsule insertions to bone. In: Woo S, Buckwalter J, eds. *Injury and Repair of the Musculoskeletal Soft Tissue.* Park Ridge, IL: American Academy of Orthopaedic Surgeons; 1988:129-166.
37. Yeh WL, Lin SS, Yuan LJ, Lee KF, Lee MY, Ueng SW. Effects of hyperbaric oxygen treatment on tendon graft and tendon-bone integration in bone tunnel: biochemical and histological analysis in rabbits. *J Orthop Res.* 2007;25(5):636-645.
38. Youn I, Jones DG, Andrews PK, Cook MP, Suh JK. Periosteal augmentation of a tendon graft improves tendon healing in the bone tunnel. *Clin Orthop Relat Res.* 2004;419:223-231.