Large Experimental Segmental Bone Defects Treated By Bone Transportation With Monolateral External Distractors

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ABSTRACT

Monolateral frames were applied to five dogs and ten lambs for treatment of large segmental bone defects (LSBD) surgically induced in one of their femoral diaphyses. Reconstruction was attempted by bone transport, as developed by Ilizarov. Mono-lateral frames were used to minimize the drawbacks of Ilizarov's circular device. Radiographic, computed tomographic, and histologic studies were performed. The skin and soft tissues were not a major obstacle for the longitudinal migration of the screws during bone transport. Four months after the operations, healing and remodeling of the bone defect was always satisfactory. Histologically, the repair of the lengthened segment followed an intramembranous ossification pattern in its central arcas and in the periphery as well. At the end of the experiment, the new induced bone had a virtually normal diaphyseal bone appearance. Bone transport for the treatment of experimental LSBD can be completed in monolateral frames.

INTRODUCTION

To date, autografts and allografts are the most commonly used methods in the western world for reconstruction of large segmental bone defects (LSBDs) caused by trauma, infection, or tumor resection. Another alternative, based on the detachment of a small bone fragment from one of the ends of the bone defect, followed by a slow longitudinal transport to the other end, was first proposed by Ilizarov.[6] Bone transport is achieved by means of a circular-shaped external fixator-distractor, and new bone is expected to be formed at the distraction zone.

The Ilizarov concept seems to have important advantages over other methods. Thus, good bone consolidation is usually obtained without the need of bone grafting or internal fixation methods. Despite these advantages, Ilizarov's circular external device also has certain drawbacks, such as its bulkiness, the difficulty of its placement and postoperative management, and the transfixing system used.

In an attempt to minimize the disadvantages of Ilizarov's device, the authors applied monolateral frames for treatment of experimentally induced LSBDs. Monolateral devices are more comfortable for the patient, they are simple to place and manage, and they require no pin transfixion. Preliminary data confirmed the reliability of these monolateral frames for bone transport after Ilizarov's technique.[4] In this study, the authors extended the experiment to analyze morphologically and histologically the viability and particularities of the new bone formed after bone transport.

MATERIALS AND METHODS

Five male mongrel dogs, six to 12 months old, and ten male Merino lambs, half of which were six months old and the other half 12 months old (mature skeletons), were used in this study. In all cases, the experiment consisted of the attempted reconstruction of a previously performed 4- to 5-cm segmental bone defect (20-25% of the femoral length) in one of the femoral diaphyses of the animals, following Ilizarov's concept[6] but using monolateral distraction-compression frames (Fig. 1). Immediately on removal of the diaphyseal femoral segment, three pairs of screws were inserted into the femur. A percutaneous osteotomy between the proximal and intermediate pairs of screws was then performed to detach a small bone cylinder from the proximal femur. The body of the mono-lateral frame was then placed and adjusted.

Two different types of monolateral frames of the authors' design were applied to the animals. Both allowed the insertion of three pairs of screws, with independent longitudinal displacement of each pair of screws with respect to the other two. The first apparatus, used on the dogs, consisted of a Wagner device with a compression-distraction device attached to one of its sides. The second, used on the lambs, consisted of various parts of the threaded and smooth tubular fixator (Fig. 2). The screws for the first apparatus were 4 mm in diameter and the second 4.5 mm.

Distraction between the proximal femoral end and the detached bone fragment was started on the day after surgery at a rate of 1 mm per day (2 x 0.5 mm/day). Throughout the distraction stage, the original femoral length was maintained by blocking the proximal and distal pairs of screws. Once the transported bone fragment reached the distal portion of the femur, distraction was continued at a rate of 0.25 mm per day for 7 to 10 days. This produced compression between the transported fragment and the distal femur. Except for those animals previously killed, frames were removed one month after the transported bone fragment had made contact with the distal femur. Animals were killed at the following times: 20 days postoperatively (two animals), the end of distraction (five animals), and four months postoperatively (eight animals) (Table 1).

Results were evaluated on the basis of radiographic, computed tomographic (CT), and histologic analysis of the transported and the newly formed bone. Radiographs were taken every two weeks from the day of surgery until the animal was killed. A postmortem radiographic study was then performed on the femora, which were stripped of soft tissues. Comparative studies of femur lengths were performed preoperatively and after each animal was killed. Furthermore, CT analysis was conducted on two lambs immediately on completion of distraction.

Histologic analysis of the femur was analyzed after each animal was killed, using hematoxylin and eosin and Masson's trichromic staining techniques. Three areas were assessed in the affected femur: the distraction tissue, the transport ed bone fragment, and the compression area.

In addition, a histologic study of muscles was also performed to evaluate the response of soft tissues at the distraction area. Muscle samples were taken from the midanterolateral portion of the quadriceps. To evaluate any possible higher neurologic distraction injury, samples taken from the midanterior portion of the anterior tibial muscle were also histologically evaluated. Muscle histology was analyzed using hematoxylin and eosin, Masson's trichromic, and periodic acid—Schiff (PAS) stains.

RESULTS

Monolateral devices were well tolerated by the animals; however, dogs often bit at them, producing the consequent deterioration of some of their aluminum components. In no case was it necessary to remove the devices before concluding the experiment.

The distraction stage was completed without major problems. The skin presented no significant impediment to the gradual migration of the screws inserted into the transported bone fragment. These screws "cut through" the skin, leaving in their wake a longitudinal wound that healed proximally as the screws advanced distally.

During bone transport, and until removal of the frame, the muscles of the operated extremity showed moderate signs of atrophy as compared with the contralateral extremity. Nevertheless, these signs of atrophy were very slight at four months after surgery. As to function, knee and hip mobility of the surgically treated extremity was somewhat limited during the period in which the apparatus was placed. After the fourth postoperative month, gait and run were observed to be normal.

From the very first stages of distraction, conventional radiographic studies showed that the space created between the proximal femoral segment and the transported bone cylinder was gradually occupied by an increasingly dense, calcified tissue. Thus a tenuous opaque structure without well-defined organization was observed within the distraction space 20 days after starting distraction (Figs. 3A-3C). From the fourth postoperative week, this opaque structure took the form of lines arranged in the direction of distraction. At the end of distraction, this structure became a uniform aspect of dense, calcified tissue (Fig. 3D).

Four months postoperatively, there was a newly formed bone tissue with an appearance similar to normal diaphyseal bone. This neodiaphysis had a regular cylindrical form equal in diameter to the rest of the diaphyseal bone (Fig. 3E). Although these observations are valid for both animal groups, the bone repair process in lambs is apparently more rapid than in dogs.

To assess the architecture of this newly formed bone tissue, CT analysis was performed in two operated lamb femora. In transverse sections taken at the end of the distraction stage, the extreme ends of the lengthened bone resembled normal diaphyseal bone, with a circular calcified tissue in the periphery and an interior radiotransparent zone (Fig. 4A). However, the central area of this distraction-induced new bone had the appearance of a solid cylinder (Fig. 4B).

As to the transported bone fragment, neither noticeable phenomena of resorption nor signs of necrosis were observed radiographically at any stage of treatment. In the zone in which compression was applied, once bone transport had ceased, radiographic consolidation was obtained four months postoperatively in seven of eight animals (six lambs and one dog). One dog remained in a status of nonunion at this level.

Histologically, the repair of the space produced by distraction followed a similar pattern to that observed in bone lengthening by diaphyseal percutaneous osteotomy.[2] Thus, 20 days after starting distraction, this space was occupied by a highly vascularized fibrous tissue, with collagen fibers arranged parallel to the direction of distraction (Fig. 5A). At the end of distraction, primarily intramembranous ossification occurred; however, scattered islands of endochondral ossification formed. This process had apparently begun at the extremities of the distraction space as well as at its periphery, where ossification was similar to periosteal desmal ossification (Figs. 5B and 5C). By the fourth postoperative month, ossification was complete in all animals. Noteworthy, this newly formed bony structure exhibited cortical bone at the periphery and some

cancellous bone in its interior, surrounding a central tubular cavity. In a panoramic histologic view, this new bone resembled normal diaphyseal bone (Fig. 5D).
Whenever observed, the transported bone fragment presented a viable histologic picture, i.e., it was composed of normal living bone tissue.
The four-month postoperative histologic assessment of the compression site disclosed, in seven animals, clear signs of consolidation, although with significant sclerosis at the contact line. In the dog with radiographically visible nonunion, a pseudoarthrosis with few signs of reparative osteogenesis was observed.
As to muscular histology, the only significant feature in the quadriceps of the operated extremity, compared with the contralateral side, involved a slight inflammatory reaction, at the time of conclusion of distraction and four months after surgery. Furthermore, a moderate muscle fiber atrophy caused by disuse (not neurogenic) was a common finding in the quadriceps of the surgically treated leg, particularly at the end of distraction. The anterior tibial muscle of the surgically treated side was considered normal when compared with the contralateral anterior tibial muscle, both at conclusion of distraction and at the fourth postoperative month.
The only complications worthy of mention involved sporadic pintract infections, which in no case threatened the continuity of the experiment.

DISCUSSION

Since Ilizarov[6] described his method of bone transport for treating LSBDs, good results have been achieved using his circular external device[3,7] or other variants.[1,5,10] All of these frames, however, share common drawbacks of transfixing systems such as bulkiness, complicated mounting, and difficulties in postoperative management. This feature prompted the authors to develop another type of external device that would minimize these drawbacks while still maintaining the advantages of Ilizarov's original concept for the treatment of LSBDs.
The reason for using two animal models was merely circumstantial. In the authors' opinion, lambs are a better animal model for this type of experiment because of their docility and availability of the gender, size, age, and breed desired.
The authors' initial experience using mono-lateral frames to treat LSBDs has been satisfactory.[4] In addition to the crucial advantage of nontransfixion, monolateral frames are easier to mount and manage postoperatively, compared with Ilizarov's apparatus or other similar devices. This experiment shows the feasibility of monolateral frames for bone transport.
One of the authors' a priori major concerns was related to how the skin, muscles, and other soft tissues would tolerate the longitudinal migration of the pair of screws inserted in the bone fragment to be transported. With progressive distraction, the screws were cutting the skin and producing a longitudinal wound that healed proximally as the screws passed. There was neither telltale skin tension at the zone of distraction nor redundant skin or folds at the compression site.

Recently, the authors have been using a specially designed screw with cutting edges and a tear-drop cross-section. This modification seems to facilitate the progressive migration of the screws through the soft tissues. Furthermore, bone transport using monolateral frames induces no significant deleterious effects on the soft tissues at the distraction level, which was confirmed by muscle histology.
On the basis of observations made, the reconstruction of the lengthened segment can be radiographically and histologically considered similar to that seen in experimental and

clinical bone lengthening by diaphyseal percutaneous osteotomy.[2] No significant radiographic or histologic differences could be found with respect to the osteogenic regenerative activity in immature lambs surgically treated at six months of age compared with the 12-month-old ones. Age differences would probably need to be greater if conclusive data were to be established concerning their influence on osteogenic potential using Ilizarov's concept.

The transported bone fragment apparently maintains its blood supply, given that neither radiographic nor histologic evidence of bone ischemia could be observed during the transport stage. Nevertheless, consolidation at the compression site appears to be more difficult, and even though bone union was obtained in most animals, this union was not as satisfactory as would have been desirable.

Although the results of this experiment seem to be promising, further research is needed to optimize this alternative for treatment of LSBDs. The basic concern now is to assess the reparative osteogenic activity, structure, and mechanical properties of the new bone induced at the reconstruction site by the Ilizarov method compared with other techniques such as autografts and allografts.

The main disadvantage of the bone transport technique is that the patient must usually wear the external distractor in place for a long period. This period can be shortened by performing the bone transport over an unreamed, interlocking intramedullary nail, which works as a guide and a bone stabilizer. Using this technique, developed in Germany by Raschke and collaborators,[9] the external distractor can be removed virtually at any time during the treatment.

Treatment of LSBDs secondary to trauma, tumor resection, old infection, and repair of congenital pseudoarthrosis may be within the range of future clinical indications for this method.

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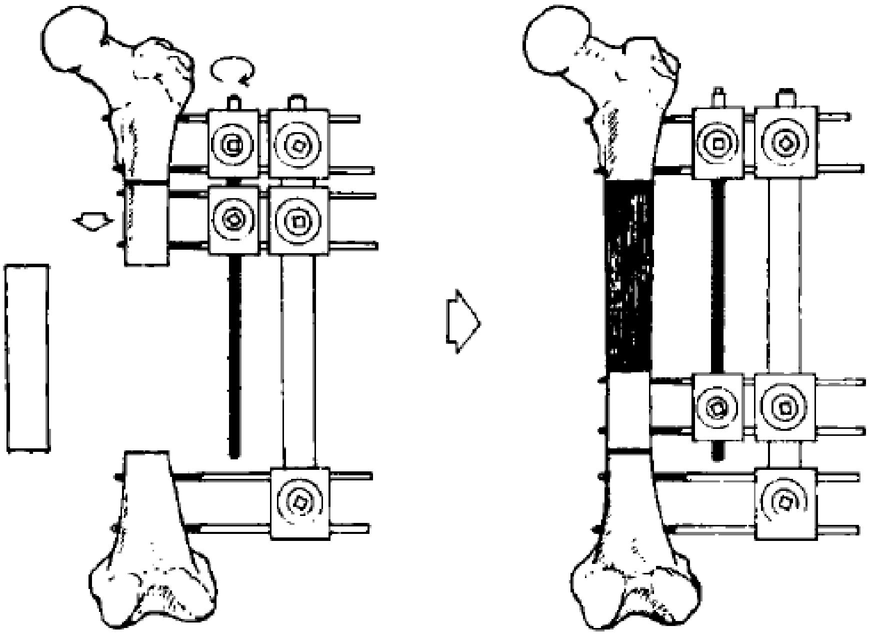


Figure 1. Schematic representation of the experimental model. Left scheme: after resection of a large diaphyseal segment and detachment of a small bone cylinder form the proximal end of the defect, a gradual distal transportation of the cylinder is performed (small outlined arrow) by turning a bolt placed in the compression-distraction device (curved arrow). Right scheme: the transportation ends when the detached bone cylinder reaches the distal end of the defect. Ideally, after the transportation the distraction area is completely occupied by newly formed bone (shaded zone).

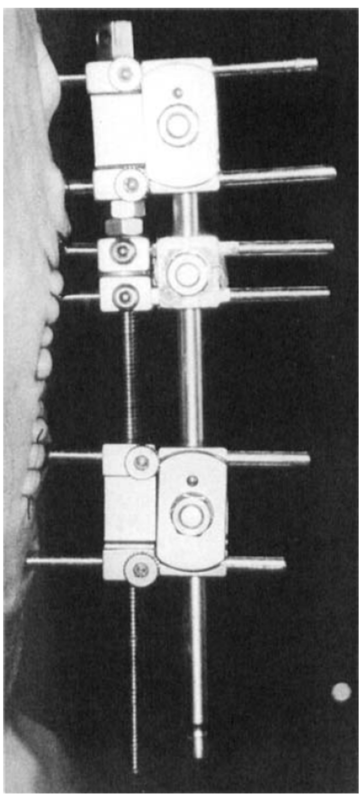
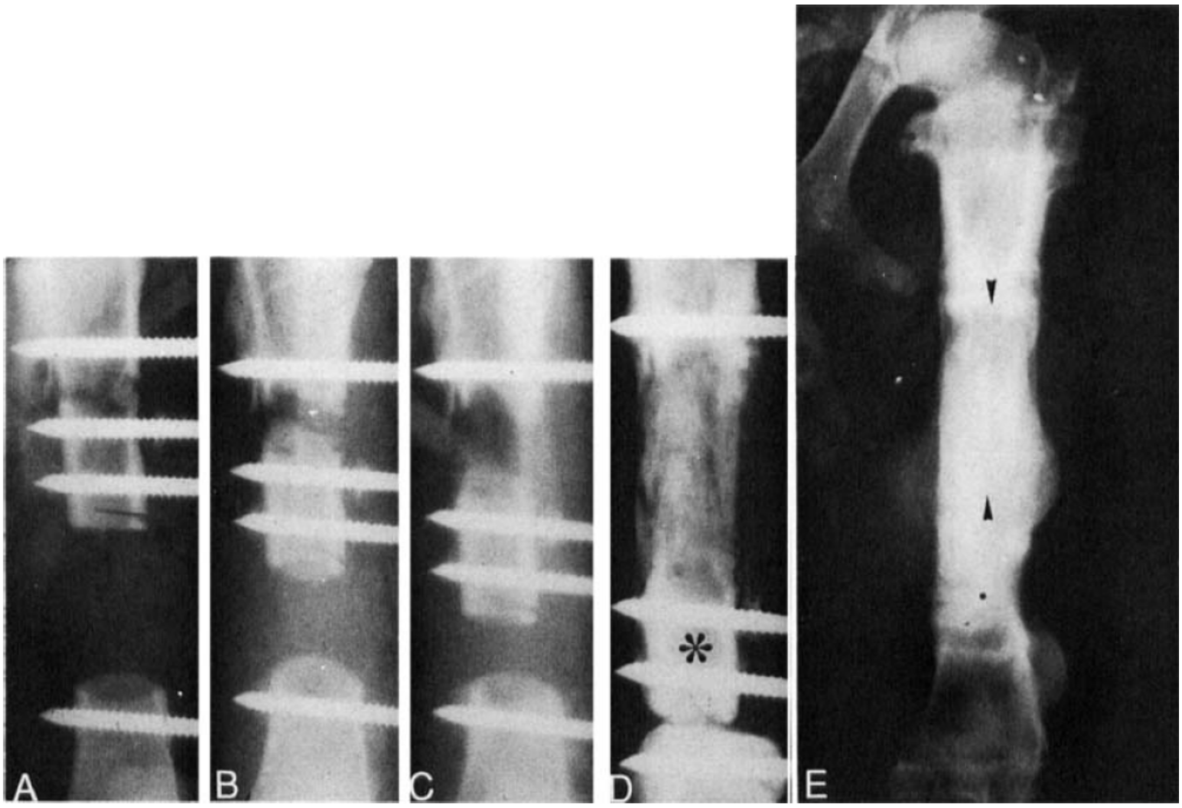
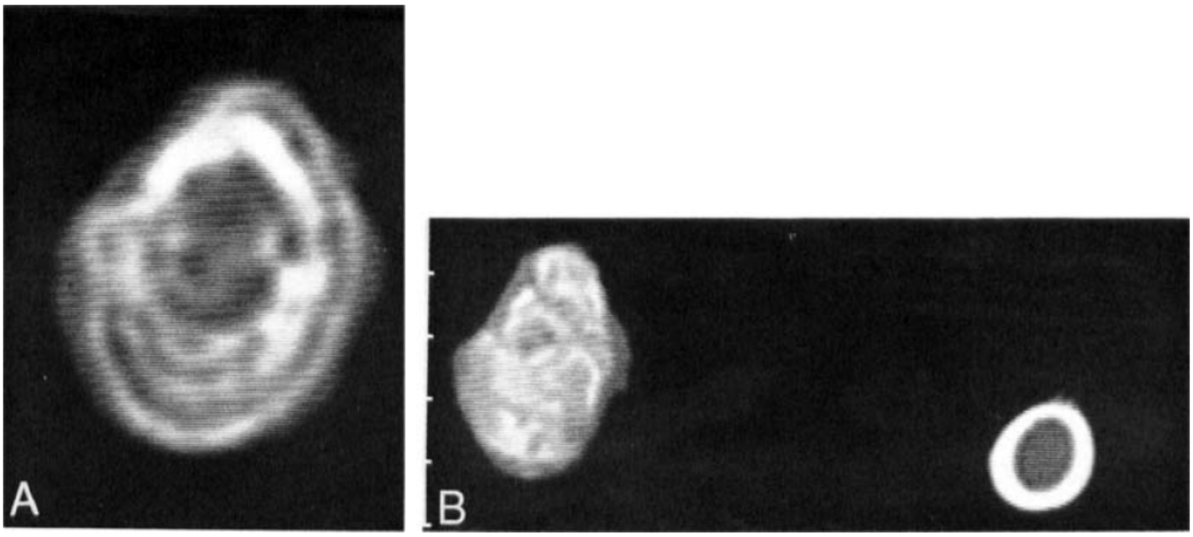


Figure 2. Monolateral frame used in the experiment.



Figures 3A-3E. Radiographic stages of the experiment. (A) Immediately postoperative. (B) Ten days postoperatively. (C) Twenty days postoperatively. (D) Forty-five days postoperatively, just at the end of the transportation of the bone cylinder (asterisk). (E) At the end of the experiment, four months postoperatively. The newly formed bone has been marked in between the arrows. Consolidation at the compression site can be observed.



Figures 4A and 4B. A CT study at the end of distraction. **(A)** Transverse section at the proximal end of the distracted segment. (B) Aspect of the central area of this newly formed bone compared with the same level in the contralateral femur.

Figures 5A-5D. Histologic pictures show some features of the new bone induced by bone transport. (A) Fibrous reparative tissue, 20 days postoperatively. (Stain, Masson's trichrome; original magnification, x4.) (B) lntramembranous ossification at the distal end of the distracted segment (45 days postoperatively). (Stain. Masson's trichrome: original magnification, x10.) (C) Periosteal intramembranous ossification in the periphery of the distracted segment (45 days postoperatively). (Stain. Masson's trichrome: original magnification, x 10.) (D) Four months after surgery, the new bone (arrows) resembles a normal diaphyseal bone. (Stain, Masson's trichrome: original magnification, x 10.)

Table 1. Grouping of Animals			
Timing of Killing of Animals	Animals		
	Dogs n = 5	Lambs (6 month old) n = 5	Lambs (1 year old) n = 5
20 days postoperatively	1	1	—
End distraction	2	2	1
4 months postoperatively	2	2	4