Comparison of cyclic compression, cyclic distraction and rigid fixation

Bone healing in rabbits

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A tibial osteotomy was created in rabbits and was fixed with an external fixator. The rabbits were divided into 3 groups in which cyclic distraction, cyclic compression and rigid fixation were applied. Fracture healing was similarly enhanced in the groups with cyclic compression and cyclic distraction. Axial cyclic movements seem to stimulate bone healing, regardless of the direction of the applied force.

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Many reports state that a cyclic compression force applied to a fracture site stimulates bone healing (Sarmiento 1967,1970,1972, Sarmiento and Schaeffer 1977, De Bastiani et al. 1984, 1986, Lazo-Zbikowski et al. 1986). There are also reports stating that the application of a controlled axial micromovement improves bone healing (Goodship and Kenwright 1985, Kenwright and Goodship 1989, Kenwright et al. 1991, Wallace et al. 1994, Noordeen et al. 1995), but it has not been proved that axial micromovement stimulates the process of bone healing, regardless of the direction of the movement, because a comparison was made only between cyclic compression movement and rigid fixation.

We tried to clarify whether fracture healing is enhanced by axial micromovement, regardless of the direction of the movement.

Animals and methods

The experimental apparatus developed for this experiment consists of an external fixator and an actuator applying cyclic movement. The frame of the external fixator, made of aluminum (A2017), could be locked firmly and unlocked easily when applying the cyclic movement (Figure 1). The device could be applied to the tibia of a rabbit.

The actuator was activated by a step-motor with a feedback system using an encoder, and could provide a well controlled axial cyclic movement. The maximum force of the actuator was 400N. When cyclic movement was applied, the animal was placed in a box, keeping the operated lower leg outside the box, and the external fixator was connected to the actuator, which was controlled by a computerized controller. A force transducer built into the actuator made it possible to measure the resisting force during a cyclic movement.

The external fixator was applied to a 6-mm steel rod it would be applied to a tibia of a rabbit and connected to the actuator. Various amplitudes of movement were used in the external fixator and the resisting force was measured to determine the relationship between the amount of deformation of the external fixator and the resisting force.

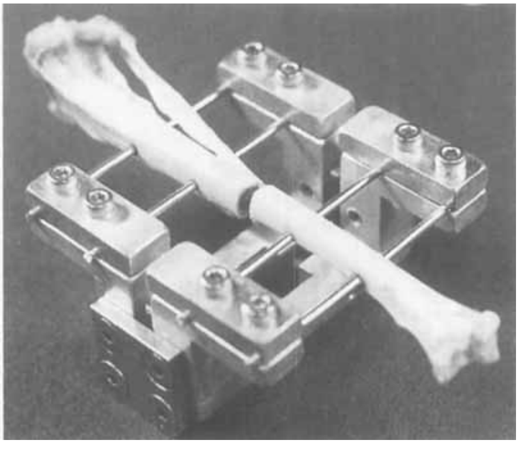

Figure 1. One tibia of a rabbit was fixed to the external fixator with four 1.8 mm Kirschner wires, spaced at 16 mm, 24 mm, and 16 mm. The distance between the side-clamps was 40 mm, and the tibia was set in the center of the Kirschner wires. A 3-mm gap was made by resecting a bone segment.

30 skeletally mature female Japanese white rabbits weighing between 3.4 and 4.0 kg were randomly divided into 3 groups.

Under general anesthesia and aseptic conditions, four 1.8-mm Kirschner wires were inserted into the tibia, using a template to maintain a constant geometry. Skin and periosteum were cut longitudinally and a transverse mid-shaft double osteotomy was performed, using a specially prepared double-blade bone saw. A 3-mm gap was made by removing the bone segment between the two osteotomies. After the osteotomy, the external fixator was applied to the Kirschner wires. Then the gap between the sections was measured to confirm that it was 3-mm wide.

In groups 1 and 2, controlled axial cyclic movement was applied to the external fixator by means of the actuator. The cyclic movement started 1 week after the operation and continued daily for 4 weeks.

The parameters for applying the cyclic movement were as follows: half-wave of sine curve; frequency, 0.5Hz; amplitude, 1.0 mm; duration, 100 seconds per day. A frequency of 0.5Hz is approximately the same as that of physiological walking. At the beginning of stimulation, the maximum strain at the fracture site was 33%, which does not damage tissue (Goodship and Kenwright 1985) and is higher than the 24% strain which increased the rate of division of osteoblasts in vitro (Buckley et al. 1988). 50 cycles of movement (100 seconds) per day were used, because the bone mineral content of intact bone showed a maximum increase after the application of a minimum of 36 cycles of strain (Rubin and Lanyon 1987). With this experimental system, although the amount of movement of the external fixator was computer-controlled to move precisely 1 mm, the actual motion between the bone fragments decreased and the force applied to the fracture site increased during the process of bone healing—that is, as the movement between the bone fragments decreased, the deformation of the external fixator increased and more force was applied to the bone fragments.

Cyclic distraction was used in group 1, and cyclic compression in group 2. At other times, the external fixator remained rigidly locked. In group 3, the external fixator was always locked firmly and this configuration was maintained for 5 weeks. Whenever cyclic movement was applied, the resisting force was recorded simultaneously in groups 1 and 2. In group 3, the resisting force was measured only once at 5 weeks after osteotomy (just before death).

2 rabbits in group 1, 3 in group 2 and 2 in group 3 were excluded during the 5 weeks because of death or fracture at the pin site, leaving 8 rabbits in group 1, 7 in group 2 and 8 in group 3. In all 3 groups, the animals with the external fixator walked around in the cages normally and showed no sign of discomfort throughout the 5-week period. By the end of the experiment, there were no signs of infection at any pin site.

5 weeks after the osteotomy, all animals were killed with an intravenous injection of pentobarbiturate. Both hind legs were disarticulated at the knee joints and ankle joints. The adhering soft tissue was removed carefully and the tibias were stored in an airtight polyethylene container at –80 °C, pending assessment.

Anteroposterior radiograms of the frozen tibias were obtained and the osteotomy gaps were examined visually.

The bone mineral content (BMC) of both tibias was analyzed, using a dual-energy X-ray bone densitometer (QDR-1000, HOLOGIC, Massachusetts, USA). The tibias were left to thaw in the airtight polyethylene container before measurement. Both tibias were placed on the bottom of a water tank made of acrylic resin and filled with water to a depth of 5 cm. The BMC at the osteotomy site was evaluated by a special high-resolution module (scan resolution = 0.1 mm). The scan area was 30 mm in length by 40 mm in width. A 20-mm long range of interest (ROI) was set, so that the osteotomy site was at the center of the ROI. The ROI was divided into 40 segments; the most proximal segment was No. 1 and the most distal segment was No. 40. The osteotomy site was located between segments 18 and 23. The BMC of each segment of each tibia was calculated separately and then the BMC of each operated tibia was divided by the BMC of the normal tibia in the corresponding segment range, to cancel individual variations. The results were the BMC ratios.

Results

The amplitudes of the resisting force at weeks 1 and 2 were statistically significantly higher in group 1 than in group 2. After week 3, there was no significant difference between group 1 and group 2 and the resisting force reached the same level as in the normal tibia at 4 weeks. The amplitudes of the resisting force at 5 weeks in group 3 were significantly lower than those in group 1 and group 2 (Table 1).

Postmortem radiographic examination showed that all tibias were in the process of normal bone healing. There was no sign of nonunion or infection. Callus formation was more evident in groups 1 and 2 than in group 3, consequently the osteotomy gap was more pronounced in group 3 than in groups 1 and 2 (Figure 2).

Table 1. Mechanical properties of the osteotomized area at 1, 2, 3, 4 and 5 weeks

A	B	C	D	E	F	G	H	I
1	1	11.6	9–19	0.001				0.91
	2	4.9	3–7					0.96
2	1	53	39–67	0.002				0.55
	2	29	13–41					0.76
3	1	82	71–98	0.2				0.30
	2	71	53–93					0.37
4	1	101	92–114	0.7				0.12
	2	98	84–113					0.13
5	1	111	103–124			1		0.03
	2	108	97–127		0.02	0.05	0.04	0.05
	3	93	73–111					0.20

A Weeks after operation
B Group
C Average of the resisting force of each group, N
D Range of the resisting force of each group, N
P-values
E Group 1 versus group 2; Mann–Whitney's U-test
F Kriskal–Wallis test
G Group 1 versus group 2 and group 2 versus group 3; Steel–Dwass test.
H Group 1 versus group 3; Steel–Dwass test.
I Movement between the bone fragments, mm
Deformation of the newly formed tissue at oseotomy site

Table 2. BMC ratios at the fracture site, from segment 18 to segment 23

A	B	C	D	E	F	H
18	1	176	132–225		0.83	
	2	165	139–192	0.02	0.06	0.04
	3	130	63–168			
19	1	163	111–235		0.70	
	2	154	131–172	0.009	0.02	0.04
	3	111	38–150			
20	1	158	105–227		0.48	
	2	139	116–161	0.004	0.02	0.01
	3	96	33–134			
21	1	162	111–241		0.70	
	2	146	109–208	0.007	0.02	0.02
	3	101	43–135			
22	1	167	115–231		1.00	
	2	162	126–219	0.03	0.05	0.07
	3	113	35–145			
23	1	175	133–236		0.97	
	2	167	142–205	0.03	0.05	0.06
	3	127	43–159			
Sum	1	167	118–232		0.86	
	2	155	130–184	0.01	0.02	0.04
	3	114	44–148			

A Segment number
B Group
C Average of the BMC ratio of each group (%)
D Range of the BMC ratio of each group (%)
P-values
E Kriskal–Wallis test
G Group 1 versus group 2 and group 2 versus group 3; Steel–Dwass test.
H Group 1 versus group 3; Steel–Dwass test.

At 5 weeks in groups 1 and 2, the BMC ratios of all segments were more than 100% in all animals, indicating that the BMC in the operated tibia was higher than in the normal tibia, including the osteotomy gap. However, the BMC ratios showed a dip at the fracture site, and the BMC ratios in some segments in group 3 were lower than 100% in 5 of 8 animals. The BMC ratios of one animal in group 3 were apparently lower than those in the other animals, for no obvious reason.

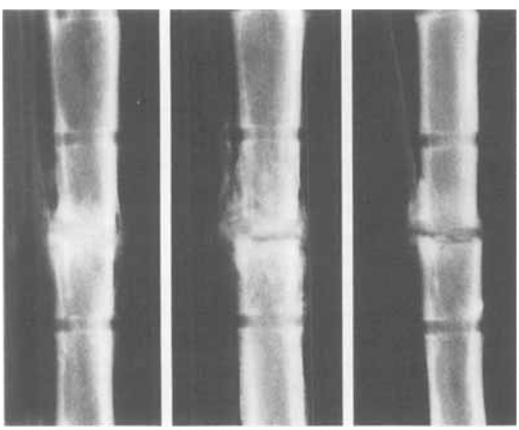

Figure 2. Typical examples of postmortem radiograms. All radiograms of the osteotomy gaps showed that the fractures were healing normally and there was no sign of nonunion or infection. Callus formation was more pronounced and the osteotomy gap was less visible in groups 1 (left) and 2 (middle) than in group 3 (right).

The BMC ratio at the fracture site, from segment 18 to 23, was significantly higher in group 1 and group 2 than in group 3; there was no statistically significant difference between group 1 and group 2 (Table 2).

Discussion

Resisting force during mechanical stimulation at weeks 1 and 2 was higher in group 1, to which cyclic distraction was applied, than in group 2, which was given cyclic compression, and movement between bone fragments was smaller in group 1 than in group 2. Therefore distraction stiffness at the fracture site in group 1 was higher than compression stiffness in group 2 at weeks 1 and 2, because only distraction force could be measured in group 1 and only compression force in group 2 in our experimental system. Two possibilities can be considered: one is that cyclic distraction stimulates fracture healing more than cyclic compression during the early stage of fracture healing and the other is that the newly formed tissue at the osteotomy site can resist tensile force rather better than compression force.

An increase in BMC does not always mean that osteogenesis is progressing. However, BMC always increases throughout the normal bone healing process. In our study, radiograms showed normal bone healing in all animals in all groups and there was no sign of infection or hypertrophic nonunion on visual and radiographic examinations. Therefore, a higher BMC ratio meant that bone healing was progressing.

The mechanical strain exceeding 1000 microstrain increased bone mineral in normal bone (Rubin and Lanyon 1987) and the rate of division of the osteoblasts was increased by 24% strain of osteoblasts (Buckley et al. 1988). Because of the large differences between these data, optimal applied strain-enhancing fracture healing might change during fracture healing. In our study, mechanical stimulation applied to the osteotomized site was changed day-by-day. Motion between the bone fragment changed from about 1 mm to about 0.001 mm and force applied to the osteotomized site changed from about 0 N to about 105 N, according to the increase in stiffness of the newly formed tissue at the osteotomized gap.

There have been no reports showing clearly both the amount of movement and force at the fracture site. Some reports (Kenwright and Goodship 1989) claim that movement or force were kept constant, but it is impossible to keep stress or strain constant at the fracture site, because stiffness of the newly formed tissue at the fracture site varies significantly during the process of fracture healing.

Among previous reports stating that cyclic compression force stimulated the process of bone healing, the cyclic compression force caused some movement between bone fragments, because the fragments were not in contact with each other. On the other hand, in the reports that bone healing was not stimulated by application of cyclic compression force (White et al. 1977, Wolf et al. 1981), the fragments moved very little when force was applied, as the bone fragments were compressed against each other prior to the application of cyclic compression force. Our findings show that axial cyclic movement at the fracture site, regardless of direction, shortens the time required for fracture healing. If the resulting cyclic movement—in other words, the deformation of the newly formed tissue within the fracture gap—is, in fact, a stimulating factor, then it is easier to explain theoretically the diverse results in previous reports.

There have been no reports stating the hypothesis that the process of fracture healing is regulated by the strain of the new tissue formed in the fracture gap, although many say that the skeletal bone mass is regulated by the strain on the bone.

According to our hypothesis, when trying to determine the optimum parameters for stimulating bone healing, more attention should be paid to the strain on newly formed tissue, which is equal to the ratio of the amount of movement to the size of the fracture gap, rather than to the amount of force applied.

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