Distraction physiolysis in the rabbit

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Axial forces across the growth plate of the upper tibia during controlled distraction were studied in 24 rabbits close to skeletal maturity. Distraction rates of 0.13, 0.26, and 0.53 mm every 24 hours were applied through a dual-frame external fixator. Strain gauges were bonded to the fixator, and axial forces were estimated prior to and following distraction. The results demonstrate two distinct patterns. In one group, forces increased to maximum values of 20–32 newtons and then suddenly decreased on subsequent distraction. This force pattern indicated fracture of the growth plate with associated hyperplasia. In the other group, lower maximum forces of 6–18 newtons were produced at the end of the distraction period, which were associated with physeal hyperplasia without fracture. These results showed that response to controlled distraction was dependent upon both the level of force acting across the growth plate and the rate of distraction; hyperplasia was achieved with lower rates of distraction up to a critical peak force above which fracture occurred.

Sledge and Noble[1] and De Bastiani et al.[2] have shown, in immature rabbits, that lengthening by physeal distraction can occur without fracture, the response being dependent upon the force applied. De Pablos et al.[3] described the response of the growth plate of lambs following fracture induced by distraction. The lowest distraction rate, 0.5 mm/day, produced the greatest viability of the growth cartilage.

The cellular response to different distraction regimes close to skeletal maturity is not known. If it were possible to lengthen without fracture close to skeletal maturity, without risk to future growth, it could be advantageous.

The aim of the present study was to monitor the forces acting across the growth plate during a controlled rate of distraction in rabbits close to skeletal maturity.

Materials and methods

Twenty-four male New Zealand white rabbits nearing skeletal maturity (mean age 39 weeks ±5 days, mean weight 3.4 ±0.32 kg) were used. Two 1.5 mm Kirschner wires were inserted into the proximal epiphysis of the right tibia and one Kirschner wire was inserted into the diaphysis. A miniature dual-frame external fixator was developed, which was clamped on to these wires (Figure 1). A template, with holes corresponding to the pin positions on the fixator, was use to obtain repeatable placement of the wires.

The dual-frame system incorporated strain gauges bonded to each arm of the fixator (Figure 2). Four gauges (Type TML FLE-1–23, Tokyo Sokki Kenkyujo Co. Ltd., Tokyo, Japan 140) were used: two active gauges and two passive gauges to achieve temperature compensation. The gauges were connected in a Wheatstone bridge circuit to a digital strain gauge amplifier (Type E-307, RDP Electronics Ltd., Wolverhampton, U.K.). Prior to use, the complete fixator assembly was mounted between aluminum blocks and calibrated on a materials testing machine (Instron model 1122, Instron Ltd., High Wycombe, U.K.).The fixators were calibrated in compression because during distraction the fixator will be subjected to compressive forces. The load applied during calibration of 0–25 N was assumed to act along the line shown in Figure 2. The response from each arm of the strain gauge was linear up to the applied load of 25 N. The total load acting between fixation points was estimated from the addition of the two forces measured through each arm of the fixator.

Three different distraction rates were applied (Table 1). In Group A a distraction rate of 0.53 mm/day was chosen to give a 5 percent increase in length over a 10-day period; this was a rate similar to one that has been shown to lead to lengthening without fracture in imma-

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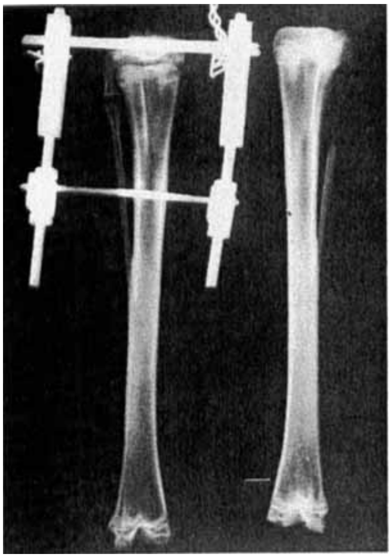

Figure 1. Postmortem radiograph of experimental and control tibiae showing position of dual-frame external fixator.

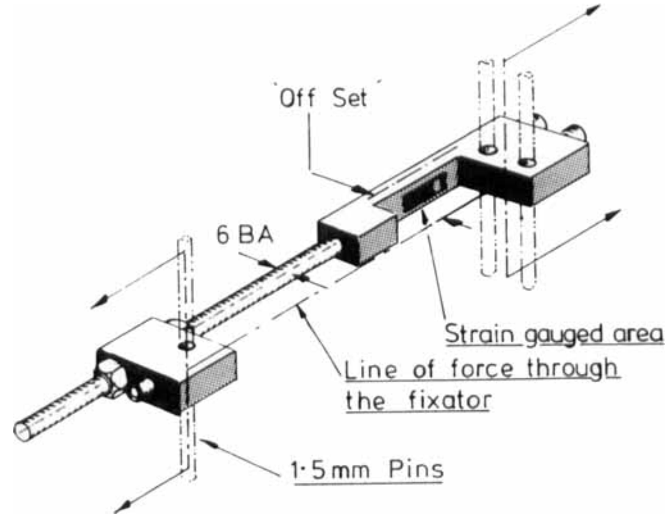

Figure 2. Strain-gauged arm of the fixator. Distraction produces a force between the pins, which is assumed to act along the line of force shown. The strain gauges are offset from this line of force, and thus measure a bending strain proportional to the distraction force.

ture rabbits[1]. However, as the rabbit matures the width of the growth plate diminishes, and thus lower distraction rates of (B) 0.26 and (C) 0.13 mm/day were also chosen to provide percentage strains across the growth plate that would be equivalent to those used in the younger rabbits. The period of distraction was chosen to provide a similar potential increase of 5.3 mm in tibial length in all three groups.

Distraction was achieved by rotating the 6 BA (British Association) nuts on the treated column of the fixator. One revolution of the nut was equivalent to a distraction of 0.53 mm. An appropriate turn of the nut was applied in a single step every 24 hours to achieve each of the three distraction rates. Strain-gauge measurements were recorded immediately following distraction and at 4 and 24 h after distraction; weekly radiographs were also taken. During the strain-gauge measurements, the animals were suspended from a sling to minimize gravitational forces.

In the sham group of 4 rabbits, the Kirschner wires were inserted and the fixator attached, but no distraction was applied. At the end of the distraction period for each of the experimental groups, the animals were killed and both tibiae were dissected out; the sham group were killed at 20 days. The lengths of the dissected tibiae and the area of the growth plate were measured. The tibiae were then fixed in buffered formalin and decalcified in 5 percent aqueous nitric acid, the end point of decalcification being determined by radiographs. Frontal plane sections were taken from each proximal epiphysis and double embedded in paraffin. Multiple sections, representative of the complete area of the growth plate, were prepared and stained with hematoxylin and eosin and examined under a light microscope.

Table 1. Distraction rates applied in experimental study

Group	Number of animals	Distraction rate (mm/day)	Days of distraction
A	5	0.53	10
B	10	0.26	20
C	5	0.13	40

Results

Peak forces were recorded immediately after each increment of distraction. Subsequently, these forces fell to approximately 80 percent of the peak value within 4 hours and remained at this level until the next increment of distraction was applied (Figure 3). Examination of the force-time behavior revealed two distinct patterns.

In all 5 animals in Group C and in 6 of 10 animals in Group B, the peak forces increased with time during the distraction period, reaching 6–18 N (Figure 4). In all of these animals, there was no histologic evidence of fracture. These growth plates demonstrated hyperplasia (Figure 5), with an increase in the number of rows of cells in both the proliferative and hypertrophic zones when compared with the undistracted contralateral growth plate.

In the remaining 4 animals in Group B and in all 5 animals in Group A, the peak forces increased with time, reaching maximum values of 20–32 N (Figure 6). The forces then suddenly decreased because of fracture (Figure 7), and subsequent distraction forces never reached the previous maximum values. The fracture pathways had certain features: the hypertrophic zone was always involved, but not exclusively, and the proliferative zone was never involved. The histology also demonstrated increased thickness of the proliferative and hypertrophic layers in each distracted growth plate. Detailed examination of the force-time characteristics for these animals indicated that immediately following the maximum force level, application of distraction actually produced a temporary reduction in force (Figure 3).

If the distraction was applied uniformly across the growth plate and the arms of the fixator were equidistant from the long axis of the bone, the individual forces in each arm would be equal. However, the results suggested an uneven force distribution across the growth plates (Figures 4 and 6), with consistently higher forces through the medial arm.

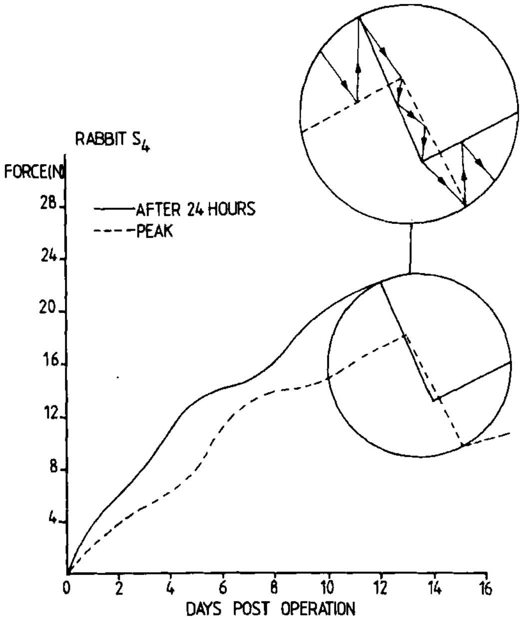

Figure 3. Peak forces and subsequent relaxation following incremental distraction of the growth plate in one of the animals in Group B. Inset details force history, as indicated by arrowed lines, around time of fracture.

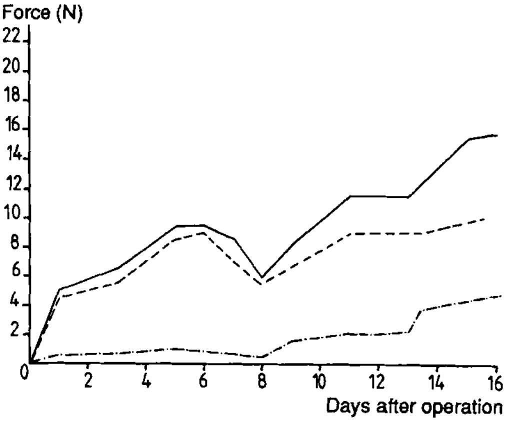

Figure 4. Force-time characteristics of one animal in Group B indicating hyperplasia of the growth plate. The total force curve is obtained from the sum of the medial and lateral components of force measured from the fixator. —— total force, - — - medial component, - · · - · lateral component.

After 20 days of distraction, there was an increase in overall tibial length when compared with the contralateral side. This was distributed evenly between the growth plate and the diaphyseal bone. A mean increase of 3.3 mm (3 percent) was observed in the hyperplastic group and 4.6 mm (5 percent) in the fracture group.

In the sham group, some irregular hyperplasia occurred adjacent to the sites of pin insertion in the peripheral zones without any effect on tibial length.

Discussion

Our results suggest that lengthening without fracture occurs up to a critical peak force, which when exceeded leads to fracture of the growth plate. It has been shown previously that if hyperplasia is produced following in vivo distraction, the growth plate exhibited a reduction in fracture strength in vitro[4]. Hence, the presence of hyperplasia, as seen in the fracture group, may influence the critical peak force.

A summary of the results of both the present and the main comparable studies on rabbits are presented in Table 2. There are several fundamental differences between the studies: namely, the age of the rabbits used, the actual growth plate subjected to distraction, and the characteristics of the distraction regime with respect to time. In our study, fracture was seen in all the cases where the distraction force exceeded 20 N, and also at a distraction rate of 0.53 mm/day. At a constant distraction force of 20 N, Sledge and Noble[1] obtained a mixed response of hyperplasia alone or fracture. De Bastiani et al.[2] produced hyperplasia alone at a distraction rate of 0.25 mm every 12 hours (equivalent to 0.5 mm/day). The absolute levels of force and distraction

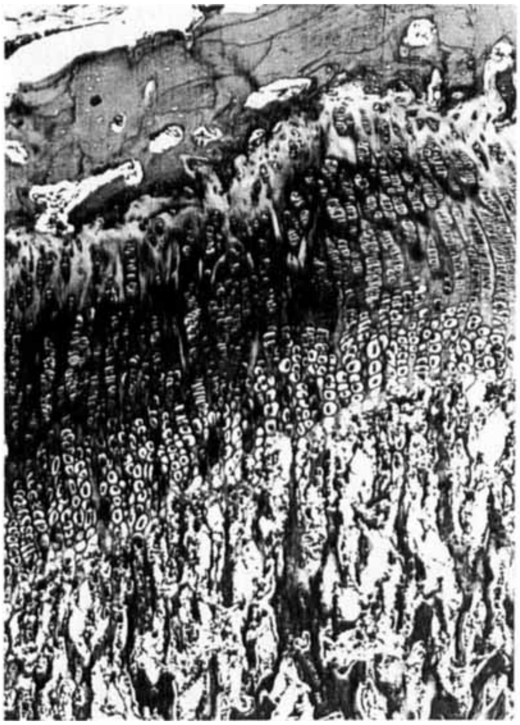

Figure 5A. Histology of a distracted growth plate at the end of the distraction period (20 days) demonstrating areas of hyperplasia in the hypertrophic and proliferative zones. (HE, x1,000)

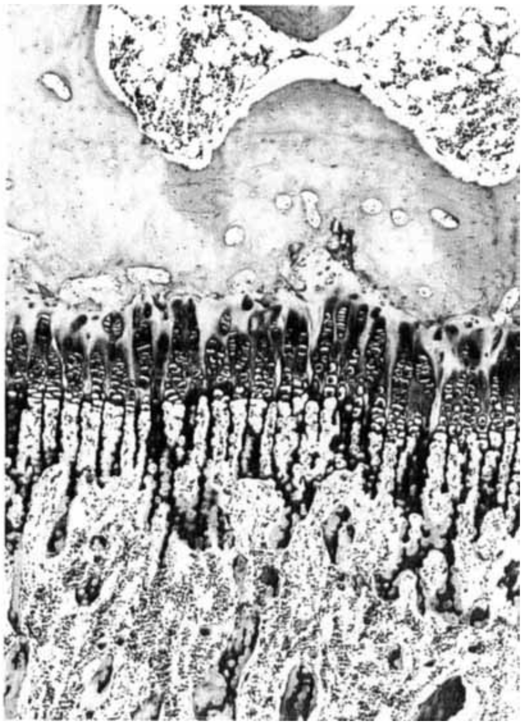

Figure 5B. Histology of the undistracted growth plate in the contralateral tibia of the same rabbit (HE , x1,000)

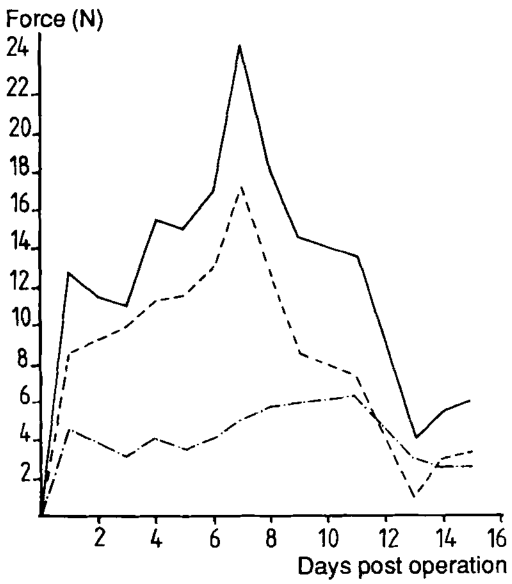

Figure 6. Force-time characteristics indicating fracture of the growth plate in one of the animals in Group B. The total force curve is obtained from the sum of the medial and lateral components of force measured from the fixator. Fracture is indicated at Day 7. ——— total force, - - - medial component, – · – · – lateral component.

rate to produce either a mixed response or fracture were lower in our more mature animals.

Our force measurement system provided a detailed account of events prior to and during fracture of the growth plate. After the initial day of distraction, there is a phase during which the force-time curves for both groups exhibited similar gradients (Figures 4 and 6). It could be postulated that this phase was coincident with the development of hyperplasia. In the fracture group, however, there is a secondary phase up to fracture represented by a sudden increase in gradient. During this phase the growth plate exhibits an increased mechanical stiffness. The consistent nature of the force behavior could well be utilized to control biological events. For example, if distraction with hyperplasia of the physis was required, force monitoring could be used to indicate the time distraction must cease if fracture was to be avoided.

The sudden decrease in force through the medial arm of the fixator reflected the overall failure of the growth plate (Figure 6). It is conceivable that the uneven force distribution may produce certain events that would be of clinical significance. First, wedging at the growth plate may occur that could lead to residual deformity[5]. The uneven distribution may also produce

Table 2. The effects of gradual distraction of rabbit growth plate

Investigation	Growth plate	Mean age of the animals (weeks)	Distraction controlled by		Biological response of the physis	
			Nominal rate (mm/day)	Force (N)	Hyperplasia (n)	Fracture (n)
Sledge and Noble (1)	Distal femur	8	-	10	12	7
			-	20	5	16
			-	40	0	8
			-	80	0	6
			-	160	0	2
De Bastiani et al (2)	Distal femur	12	0.50	-	4	0
			1.00	-	0	10
Present study	Proximal tibia	39	0.13	6–10	5	0
			0.26	10–18	6	0
			0.26	20–32	0	4
			0.53	21–31	0	5

premature failure of the medial side of the growth plate, which propagates across the growth plate resulting in a total failure at a force level below the ultimate fracture strength of the growth plate. As the fracture propagates, the effective area of the growth plate decreases, and hence subsequent distraction will result in the reduction in forces noted in the inset to Figure 3. When fracture propagation is complete, further distraction will produce forces balanced by tension in the surrounding soft tissues. The use of the present dual-sided system which can monitor forces during the distraction period is thus essential if such events are to be predicted.

Reliable and predictable lengthening without fracture carried out at a slow distraction rate leads to only a 3 percent increase in length over 6 weeks. Higher distraction rates can lead to lengthening without fracture, but near skeletal maturity, close monitoring, and modification of the distraction regime will be needed throughout to prevent fracture. It is likely therefore that fracture will be inevitable in the later stages of maturity if substantial lengthening by distraction is attempted.

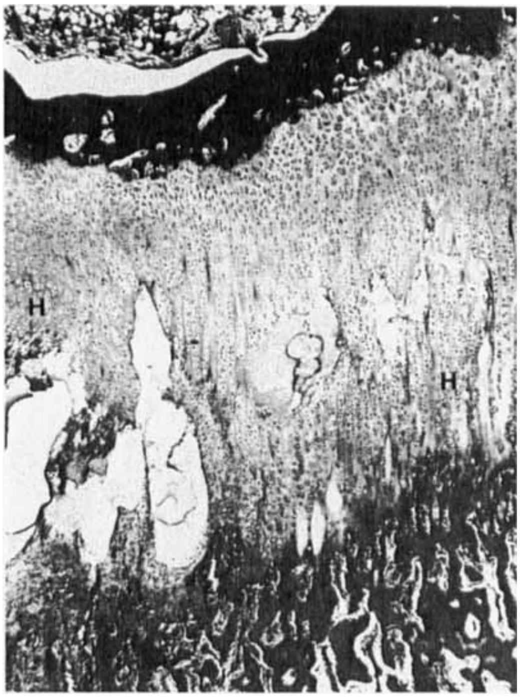

Figure 7. Histology of a distracted growth plate demonstrating fracture. Some areas of hyperplasia are evident. (HE, x360)

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