EPIPHYSEAL DISTRACTION MONITORED BY STRAIN GAUGES

RESULTS IN SEVEN CHILDREN

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Ten epiphyses in seven children underwent fixed-rate distraction of 0.25 mm twice daily in an attempt to achieve percutaneous leg lengthening by chondrodiastasis. The forces generated across the growth plate were recorded by means of strain gauges incorporated into the distractors. All epiphyses fractured before 33 days of lengthening. An average gain of 6.75 cm was achieved. Epiphyseal distraction at the lower femur produced many complications, but at the upper tibial epiphysis planned lengthening was achieved, with excellent bone production and few complications.

In 1969 Ilizarov and Soibelman of the Soviet Union reported limb lengthening by distraction epiphyseolysis, in which transverse fracture separation of the epiphyseal plate is induced by distracting the growth plate with a modified external fixator. The clinical results were impressive and have been confirmed by similar work in Europe (Monticelli and Spinelli 1981). The advantages of such a technique are considerable; it is less traumatic, requires only one operation and is not associated with non-union. The two main limitations are related to the patient's maturity. First, to achieve fracture of the epiphyseal plate it must be still open; secondly, the main proponents point out that the technique should only be used just before fusion since evidence suggests that the long-term outlook for further function is uncertain.

Although the early reports describe lengthening by fracture separation or epiphyseolysis of the growth plate, lengthening by accelerated growth without fracture may be possible. As early as 1957, having made the clinical observation that the hip trochanters were large in juvenile amputees and small in children with paralysed abductors,

Smith and Cunningham investigated the effect of tension on the tibial and metatarsal growth plates of calves. They detected a growth increase with associated plate widening. In a more detailed study Sledge and Noble (1978) found that epiphyseal lengthening without fracture was possible in the rabbit; they emphasised the importance of controlling the load applied to the growth plate, thus introducing the concept of force-dependent as opposed to rate-dependent lengthening.

The possibility of non-destructive epiphyseal lengthening is of considerable interest since there is some disagreement in published reports regarding epiphyseal function after distraction. Premature epiphyseal fusion has been noted (Ring 1958; Letts and Meadows 1978), but Jani (1975) reported disturbance of growth plate architecture with no alteration in function. This has been confirmed by Sledge and Noble (1978) and by Fishbane and Riley (1980). More recently this work has been repeated by De Bastiani et al (1986b); they recommended a fixed rate of distraction of 0.25 mm twice daily as that needed to achieve non-destructive lengthening.

In our study of epiphyseal leg lengthening we used this fixed rate in an attempt to achieve non-destructive lengthening and we measured the distraction forces involved.

PATIENTS AND METHODS

Seven patients had 10 segments lengthened (Table I). One achondroplastic had elongation of both femora and tibiae. Two femoral lengthenings were for discrepancy resulting from bacterial infection of the hip and subsequent damage to the capital epiphysis. Two tibial lengthenings were for hypoplasia, one for the absent

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Table 1. Aetiology, age and site of distraction in seven patients

Case	Sex/age (yr)	Aetiology	Site of lengthening	Discrepancy (cm)	Gain		Time on fixator (mth)	Bracing (mth)	Complications	Comment
					(cm)	percent				
1	F 13	Septic hip	Left distal femur	5	4.7	13	9	12	Fixator failure Knee stiffness Fracture	Loss of 1.5 cm following fracture
2	M 15.3	Septic hip	Left distal femur	6.5	7	18	10	5	—	—
3	M 14	Tibial hypoplasia	Left proximal tibia	5.5	5	15	8	11	Fibula migration Knee release Valgus tibia	Awaiting corrective varus osteotomy
4	M 12.5	Absent fibula syndrome	Right proximal tibia	6	5.5	18	11	8	Fracture	No loss of length
5	F 13.5	Tibial hypoplasia	Left proximal tibia	5.5	7	20	10	9	Fibula migration Re-alignment Varus tibia	Awaiting corrective valgus osteotomy
6	F 14.2	Congenital heel-buttock tether	Left proximal tibia	6	4.5	14	8	9	Failed epiphyseal separation Stiff foot	Previous complicated femoral lengthening Lengthened through metaphyseal fracture
7	F 14	Achondroplasia	Right distal femur		11.5	45	15	15	Stiff knees Bilateral fibula migration	Simultaneous femoral and tibial lengthening. Release of right equinus ankle
			Right proximal tibia		7	36	15	15	Left equinus deformity	Repeat right fibula osteotomy
			Left distal femur		11.0	43	12	15	Right equino-valgus deformity	
			Left distal tibia		7	36	12	15		

fibula syndrome and one for growth disturbance following heel-buttock adhesion. The four girls and three boys had a mean age of 13.8 years (range 12.5 to 15.3). The mean discrepancy for the femoral group was 5.7 cm (range 5.0 to 6.5 cm) and for the tibial group 5.8 cm (range 5.5 to 6.0 cm). One of the patients had previously undergone a complicated ipsilateral femoral lengthening and sustained a closed tibial fracture that had united without deformity.

Before operation all the children and their parents had detailed counselling. The predicted discrepancy was calculated where possible from Moseley's straight line graphs (Moseley 1978) or Anderson's tables (Anderson, Green and Messner 1963). Plain and long cassette radiographs of both lower limbs were supplemented with CT scans to determine patency of the epiphyseal plate and the planar surface area of the distraction zone. In view of the reported discomfort (Monticelli and Spinelli 1981), visual analogue scales for pain assessment were introduced to the children and completed in the postoperative period.

Techniques of operation. Lengthening was carried out using a modified Roehampton external fixator (Wang and Dewar 1984). The device has four components (Fig. 1): an aluminium head (A) that carries the epiphyseal pins, a threaded stainless steel rod (B), and a box-section stainless steel tube (E) that carries diaphyseal pin holders (C). The fixator is attached to the bone with 6 mm Schanz screws that are fixed to the head with methylmethacrylate cement and clamped to the pin holders. Lengthening is

Fig. 1

Fig. 2

Figure 1 – Components of the distractor: A) aluminium head that carries the epiphyseal pins; B) threaded steel rod; C) diaphyseal pin holders; D) collar, which provides 1 mm of lengthening per complete revolution; E) box section. Figure 2 – The neck of the telescopic section showing the foil strain gauges.

achieved by turning the collar (D), one complete revolution producing an elongation of 1 mm. The neck of the telescopic section included foil strain gauges (Fig. 2), which were orientated and connected so that they measured the axial forces in the bone. The gauges were calibrated on a universal testing machine before use.

Fig. 3

The force-time plot of case 4 as an example of uniphasic failure. The corresponding visual analogue scale for pain level shows a peak in association with the peak force.

The sites of distraction were the lower femoral and proximal tibial epiphyses, but in one of the achondroplastic limbs the distal tibial epiphysis was used in an attempt to minimise knee stiffness. Placement of the device was performed under general anaesthesia with radiological control. The limb was not exsanguinated unless fibular osteotomy was considered necessary. Epiphyseal pins were placed within the epiphysis parallel to the joint line through separate stab incisions. A lateral approach was used for the lower femur to avoid neurovascular damage, and medial and anterior approaches were used for the tibial epiphyses. Diaphyseal

pins were placed perpendicular to the axis of the bone to allow the fixator to be aligned parallel to the longitudinal axis.

After operation mobilisation on crutches and full weight-bearing were encouraged. All patients performed their own distraction from the third postoperative day at the rate of 0.25 mm twice daily. Visual analogue scales were completed for pain levels at one hour before and one hour after distraction for the first four weeks. Force readings from the transducers were taken every hour for the first two weeks and then immediately before and after distraction. This data was initially recorded by the nursing staff and subsequently by the patient. Distraction was continued until the required length was achieved. Once the distracted bone was sufficiently consolidated the fixator was removed under anaesthesia and a brace applied to the leg until consolidation was complete.

RESULTS

The clinical results are summarised in Table I. The mean gain in length for the unilateral lengthenings was 5.6 cm (range 4.5 to 7 cm). A mean gain of 5.9 cm was achieved for femoral lengthening and 5.5 cm for the tibial, giving a percentage gain of 16% (range 13% to 20%). The mean gains in the achondroplastic patient were 7 cm for the tibias and 11.3 cm for the femora, giving percentage gains of 36% and 44% respectively.

Biomechanical findings. Ten growth plates were distracted. Data from three growth plates were not suitable for analysis; in one separation had occurred at the adjacent metaphysis, and in two the transducers malfunctioned. Recordings were accumulated for the duration of distraction, but for the purposes of this report only the first 40 days will be discussed. The forces generated were expressed as Newtons and related to the cross-sectional area in square millimetres as determined from CT scans of the epiphyseal plate.

Two distinct force patterns were apparent: these were termed uniphasic and biphasic (Tables II and III). Four epiphyses demonstrated a uniphasic pattern. An example is shown in Figure 3, in which there is a gradual increase in the force to a maximum of 435 N (equivalent to a stress of 0.165 N/mm²) at eight days followed by an abrupt reduction. For this pattern the mean value of the maximum stress was 0.24 N/mm² (s.d. 0.77 N/mm²) at a

Table II. Biomechanical results from four epiphyses that showed uniphasic failure

Case	Epiphysis	Days to failure	Peak force (Newtons)	Stress (N/mm ²)	Peak pain by visual analogue scale (cm)
1	Distal femur	7	466	0.296	5
2	Distal femur	20	780	0.316	8
4	Proximal tibia	7	435	0.165	4
7a	Distal femur	5	315	0.182	1.3

mean of nine days. A biphasic pattern was seen in three epiphyses with two distinct peaks occurring at mean times of 10 and 20 days and at stresses of 0.2 N/mm^2 (s.d. 0.041) and 0.229 N/mm^2 (s.d. 0.062) respectively. In the example shown in Figure 4 the failure peaks occur at forces of 320 N and 345 N (equivalent to stresses of 0.153 and 0.165 N/mm^2) at 10 and 30 days respectively. There appeared to be no correlation between the mode of failure and the type of growth plate as classified by site or aetiology.

The readings from the visual analogue scales showed definite peaks of pain associated with abrupt load reductions in both the uniphasic and biphasic patterns (Figs 3 and 4) except that in the achondroplastic child, pain rarely reached above 1.5 cm of the 10 cm scale during the period of observation.

Complications. The external fixator used in the first femoral lengthening bent in its extensible segment when fully distracted, needing removal and straightening under anaesthesia. This fixator has since been used only for tibial procedures in patients with anticipated low forces. A strengthened device has been used for femoral lengthenings and most tibiae without component failure.

There was loss of alignment in the coronal plane in one femoral and two tibial lengthenings. In one case this was detected during lengthening; this necessitated realignment of the fixator under general anaesthesia. The deformity was not fully corrected. In the other two cases malalignment was not detected until the healing phase; these children are awaiting surgical correction. Two pin sites were infected with *Staphylococcus aureus*, but both responded to a course of appropriate antibiotics, and without pin removal.

The fixators remained in place for a mean of 9.3 months (range 8 to 11 months) in the unilateral

Fig. 4

The force/time plot of case 3 demonstrating biphasic failure. The corresponding visual analogue scale for pain level shows the association with the peak forces.

Fig. 5

Fig. 6

Fig. 7

Figure 5 – Case 1. Fracture through the distraction zone after removal of the distractor. Figure 6 – Case 5. Descent of the head of the fibula during tibial lengthening. Figure 7 – Case 7. Ascent of the lateral malleolus during tibial lengthening, despite fibular osteotomy.

Table III. Biomechanical results from three epiphyses that showed biphasic failure

Case	Epiphysis	Days to failure		Peak force (N)		Stress (N/mm ²)		Pain scale (cm)	
		Peak 1	Peak 2	Peak 1	Peak 2	Peak 1	Peak 2	Peak 1	Peak 2
3	Proximal tibia	10	30	320	345	0.153	0.165	10	10
7b	Distal femur	10	28	395	500	0.228	0.289	1.6	1.6
7c	Distal tibia	10	32	235	250	0.220	0.234	1.5	1.5

lengthenings and after their removal fractures within the distraction zone occurred in two cases. In one case this resulted in loss of 1.5 cm of length (Fig. 5). The other fracture healed without loss of length. After this, bracing was retained for a mean of nine months (range 5 to 12 months) after removal of a unilateral fixator. The achondroplastic child was braced for 15 months after the simultaneous femoral and tibial lengthenings.

There was dislocation of the tibio-fibular joints in four of the tibial lengthenings, two at the proximal (Fig. 6) and two at the distal joint (Fig. 7) which produced an equino-valgus deformity of the hindfoot in one. All the patients having femoral lengthening developed severe and increasing knee stiffness that only resolved with removal of the fixator. One child with a 10° fixed flexion deformity of the knee that was not corrected pre-operatively and who underwent tibial lengthening, required a posterior release of the joint during the lengthening phase. All the patients having tibial lengthening developed temporary stiffness of the hindfoot and an equinus deformity. One required release of the calcaneal tendon and posterior capsulotomy of the ankle. Some midfoot and forefoot stiffness developed during distraction, but this resolved with time.

DISCUSSION

Instrumented epiphyseal distractors have been used during growth plate distraction to quantify the loads required to produce failure of the plate (Monticelli and Spinelli 1981); their use during 'chondrodiastasis' has not previously been reported. Using the recommended rate of 0.25 mm twice daily (De Bastiani et al 1986b), all the epiphyses demonstrated a fall in the stress. The uniphasic pattern represents abrupt failure of the whole epiphyseal plate occurring after a mean of 4.5 mm of distraction. In the biphasic pattern the first peak is consistent with hemifailure of the epiphyseal plate and the second peak with complete failure including the perichondrial ring (Jones, Poliakoff and Bright, personal communications 1986). In the three epiphyses demonstrating biphasic failure the first peak occurred after 5 mm of distraction and final separation at 10 mm. The fall in stress was associated with an increase in pain. This is believed to be due to an increase in tension in the periosteal sleeve. Pain was severe in some cases, requiring narcotic analgesia for adequate control.

The concept of 'chondrodiastasis' or non-destructive

lengthening in which the epiphyseal plate is merely stretched is designed to overcome the main shortcoming of growth plate lengthening. In our study all growth plates separated within 32 days and chondrodiastasis was not observed. The lengthening rate of 0.25 mm twice daily has been claimed to stretch the growth plate (De Bastiani et al 1986b), and avoid the hazards of fracture separation. This rate of lengthening is based on distraction studies in the immature lower femoral epiphysis of rabbits (De Bastiani et al 1986a) and was used in the present study. It is not clear whether a figure derived from animal studies is appropriate for use on normal human epiphyses. In our series, physeal distraction was carried out in only two normal epiphyses, the remainder of the patients having shortening secondary to either structurally abnormal growth plates or congenital anomalies of the limb. It is unlikely that a fixed rate of distraction will be suitable as there are sex and age dependent changes in the mechanical characteristics of growth plate cartilage (Bright, Burstein and Elmore 1974) which are not taken into account.

The mean force for the whole group at final failure of the growth plate was 0.258 N/mm². From our limited data it would be incorrect to attempt to correlate failure loads with the aetiology of the length discrepancy or the site of lengthening. However it may be observed that to avoid plate failure the stress should be maintained at less than 0.153 N/mm² – the lowest stress which caused failure.

On the basis of our study it seems prudent to advise that non-destructive lengthening of the epiphyseal growth plate cannot be achieved by using a fixed rate of distraction of 0.25 mm twice daily. This rate of distraction in pre-adolescent children is likely to result in fracture separation of the growth plate and subsequent cessation of function.

Our complication rate was similar to that reported for shaft lengthening (Armour and Scott 1981; Hood and Riseborough 1981) and the severe knee stiffness during distal femoral lengthening, resulting from intracapsular pin placement, is a matter of concern. The most significant advantage was that no cases of non-union were seen. Some of the problems we encountered might be associated with the initial use of a new technique, but many are well-established sequelae of limb length correction.

At our present state of knowledge we feel that femoral lengthening by callus distraction after previous

osteotomy may be a preferable method. Tibial lengthening by physal distraction, however, was satisfactorily achieved at the upper tibial epiphysis shortly before natural physal fusion. The new bone production at this site was excellent and good lengthening was obtained, making this method a reasonable alternative to diaphyseal lengthening. Osteotomy of the fibula is recommended as separation of the fibular epiphyses may not occur spontaneously.

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