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REMODELLING AFTER DISTAL FOREARM FRACTURES IN CHILDREN

I. *The Effect of Residual Angulation on the Spatial Orientation of the Epiphyseal Plates*

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The effect of residual fracture angulation on the distal radial and ulnar epiphyseal plates was studied in children aged 1 to 15 years. Thirty-eight fractures located in the distal fifth of the forearm bones were observed for 1 to 25 months after the fractures had healed. The forearms were examined radiographically on two to five occasions and the inclinations of the epiphyseal plates in relation to the long axis of the proximal fragments were measured.

The results showed that an abnormal inclination of the epiphyseal plate after healing of a distal forearm fracture induced an alteration of growth in the epiphyseal plate. The redistribution of growth tended to correct the abnormal inclination. The rate of correction followed an exponential course.

The age of the child at the time of the fracture and the distance from the fracture to the epiphyseal plate did not influence the capacity for correction.

Key words: child; epiphyses; forearm; fracture; growth; remodelling

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The mechanisms behind the remodelling process after fractures are still not clarified. The main reports have focused on the correction of angulation at the fracture site (König 1908, Önne & Sandblom 1949, Attenborough 1953, Ghandi et al. 1962, Miyagi & Murayama 1964, Lanzi 1965, Bennek & Steinert 1966, Grewe & Niemann 1966, Nonnemann 1969, Spissak et al. 1969, Swaan & Oppers 1971, Hansen et al. 1976, Högström et al. 1976). Very little attention has been paid to the possible role of the epiphyseal plate in the remodelling process. Steinert (1966) suggested, but without concrete evidence, that the epiphyseal plate might be of importance. Pauwels (1975) observed a normalization of the inclination of the subcapital epiphysis of the femur in a case with a subtrochanteric fracture which had healed with angulation. However, the first consistent evidence was given by Ryöppy & Karaharju (1974), who showed in an experimental study in rats that the epiphyseal plates changed their direction of growth after fractures uniting with residual angulation.

In the present study the contribution of the epiphyseal plate to the remodelling process was investigated in more detail. The most common fracture in the child, i.e. the distal forearm fracture (Ghandi et al. 1962, Ehalt 1961, Wong 1965), was chosen. The aim was to study the effects of residual angulation in

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healed fractures on the spatial orientation of the distal epiphyseal plates of the radius and ulna.

MATERIAL AND METHODS

Repeated radiography of 38 wrists and forearms was performed in 37 children with residual angulation after healing of fractures in the distal fifth of the forearm. The patients were selected from all cases of distal forearm fractures in children treated at the Department of Orthopaedic Surgery in Umeå during the years 1970–73. The selection was made so as to obtain a representative series with regard to different ages, degrees of residual angulation and directions of residual malposition. The radiographs at the time of healing of the fracture (removal of plaster) were used as a basis for the evaluation. Both wrists of the patients were then re-examined radiographically on one to four occasions. The change in inclination of the distal radial epiphyseal plate was measured in the lateral (dorso-volar plane) and frontal (radio-ulnar plane) projections. The distal ulnar epiphyseal plate was studied in the lateral (dorso-volar plane) projection. Further details of the characteristics of the material are given in Table 1.

Radiographic technique at re-examination

The fractured and contralateral wrists were examined on a skull table (film-focus distance 70 cm). When possible, the arm was positioned with 90° abduction in the humeroscapular joint and the elbow joint flexed 90° (Movin & Karlsson 1968). The frontal and lateral projections were achieved by pronation and supination of the forearm.

In the radiographic examinations only films with a difference in rotation of 10 degrees or less were accepted for the study (Friberg & Lundström 1977). No correction for differences in rotation was made as a rotational difference of 10 degrees will introduce an error of less than 0.5 degrees for an angulation of the epiphyseal plate of 30 degrees.

Measuring technique

The inclinations of the distal radial and ulnar epiphyseal plates in relation to the central axis of the distal third of the proximal fragments were measured on superimposed drawings of the

Table 1. Distribution in the series of the variables used for the statistical analysis of the results. Means and standard deviations are given where not otherwise stated. Ranges in brackets

	Angulations in the radius, dorso-volar plane		Angulations in the radius, radio-ulnar plane		Angulations in the ulna, dorso-volar plane	
No. of examinations	No. of fractures	Observation time, months	No. of fractures	Observation time, months	No. of fractures	Observation time, months
1	36		14		7	
2	36	6.4 ± 4.5	14	5.0 ± 3.4	7	5.5 ± 3.7
3	17	11.5 ± 4.8	5	7.8 ± 4.0	3	1.1 ± 0.6
4	5	15.6 ± 5.9	2	6.5 ± 0.7	-	
5	2	16.5 ± 0.7	1	16	-	
Totals	96		36		17	
Age at fracture, years	9.4 ± 3.6 (1-15)		9.8 ± 3.3 (3-14)		7.1 ± 3.1 (3-10)	
Sex, no. of boys/girls	25/11		12/2		4/3	
Side, no. of right/left	19/17		7/7		4/3	
Primary angulation of the epiphyseal plate, degrees	14.2 ± 8.3		10.1 ± 4.7		14.1 ± 7.9	
Type of fracture,	No.		No.		No.	
Torus	11		2		1	
Greenstick	10		2		2	
Complete	15		10		4	
Treatment = plaster of paris	No.		No.		No.	
+ No reposition	18		2		2	
1 reposition	13		7		3	
>1 reposition	4		3		2	
Op. reduction	1		2		0	
Distance of fracture from the epiphyseal plate in per cent of total diaphyseal length	11 ± 5		11 ± 5		11 ± 7	

radiographs. Furthermore, when possible, the longitudinal growth produced by the epiphyseal plates was assessed. The prerequisite for adequate measurements was that the inner borders of the cortex were used as reference points, as the outer borders of the cortex in most instances were altered by new bone formation and resorption. The inclination of the epiphyseal plate in the fractured wrist was expressed as the angle between the epiphyseal plates in the fractured and normal contralateral wrists (Friberg & Lundström 1976) (Figures 1 and 2). In the bilateral case an angle of 90 degrees between the epiphyseal plate and the central axis of the distal third of the bone was chosen to represent the normal inclination.

In order to ascertain if there occurred any major correction of the angulations of the fractures of the radius, the shortest distances from the midpoints of the epiphyseal plates to the central axis of the proximal fracture fragment were studied.

The total error of the measuring procedure was evaluated by repeated measurements and was 1.2 degrees ± s.d. = 0.4 degrees for the inclinations of the epiphyseal plates and 0.9 millimetres ± s.d. = 0.5 millimetres for the longitudinal growth at the epiphyseal plates.

Statistics

The means, and standard deviations are given. The differences between group means were analysed by the z and *t*-tests. Standard computer programs (BMD02R) were used for the regression analysis. The influence was not considered to be significant with $P > 0.05$.

RESULTS

General findings

With few exceptions the distal epiphyseal plates of both the radius and the ulna were found to alter their inclinations in relation to the long axis of the bones. No tendency to correction of the inclination of the epiphyseal plate was found in five fractures of the radius with minimal primary angulations (mean 4°, range 2°–7°). Without exception, changes in inclination tended towards normalization of the spatial orientation of the epiphyseal plates (Figures 1, 2 and 3).

No reduction in the shortest distance between the midpoints of the epiphyseal plates and the central axis of the proximal fracture fragments occurred. This showed that the alternation in the inclination of the epiphyseal plates was not due to a correction of the angulation in the fracture.

Capacity for correction of abnormal inclinations of the epiphyseal line expressed as a function of time

Mean correction expressed as degrees/month. The mean correction at the radial epiphyseal

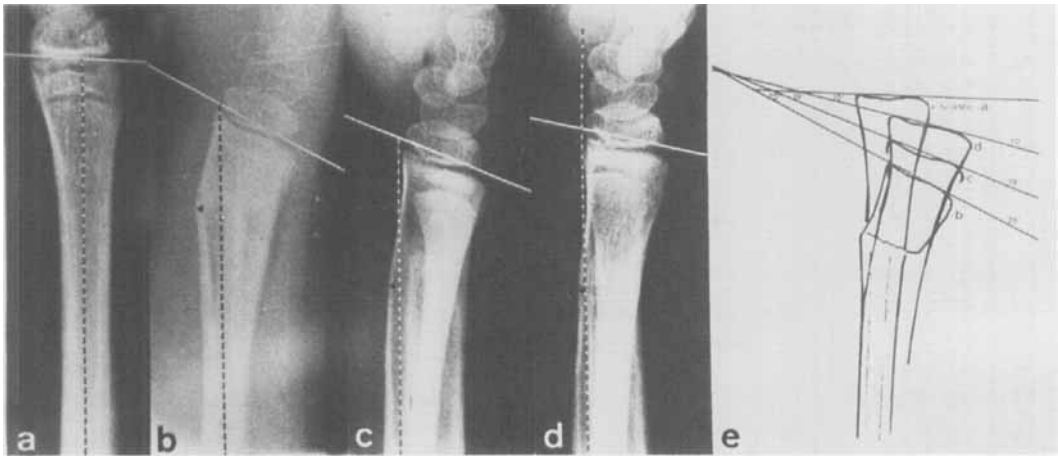

Figure 1. The change in inclination of the epiphyseal plate in a case with dorsal angulation of the proximal fragment. (a) Unfractured control side. (b) Fractured side – at the time of removal of the plaster. (c) Fractured side – 7 months' observation. (d) Fractured side – 14 months' observation. (e) Superimposed drawing of (a)–(d).

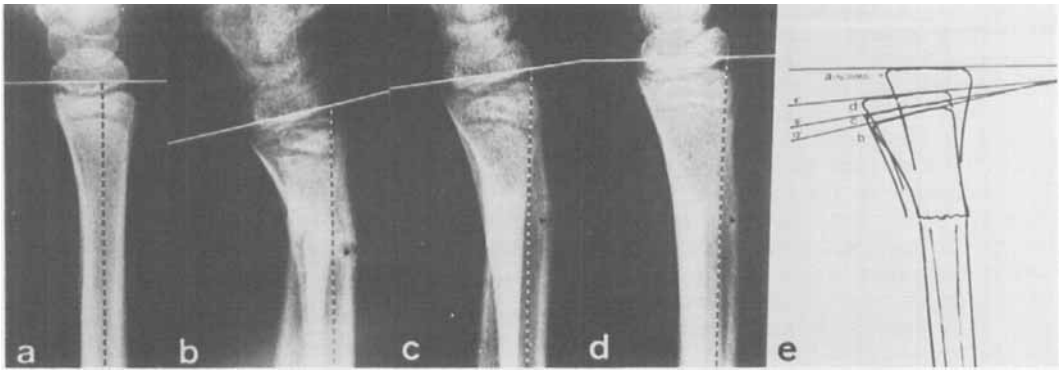

Figure 2. The change in inclination of the epiphyseal plate in a case with volar angulation of the distal fragment. (a) Unfractured control side. (b) Fractured side – at the time of the removal of the plaster. (c) Fractured side – 3 months' observation. (d) Fractured side – 10 months' observation. (e) Superimposed drawing of (a) – (d).

plate was calculated to be 0.9 degrees/month (60 observations) in the dorso-volar plane and 0.8 degrees/month (22 obs.) in the radio-ulnar plane. The ulnar epiphyseal plate showed a correction of 0.8 degrees/month (10 obs.) in the dorso-volar plane (Table 2). No differences existed between the two different projections of the radius or between the radius and the ulna.

When the material was divided into groups with regard to the residual angulation after healing (0°–4°, 5°–14°, > 15°), it was found that the rate of correction was higher in the groups with larger primary angulations (Table 2). Furthermore, the shape of the graphic curves suggested a tendency to a reduction in the rate of correction as normalization proceeded (Figure 3).

Table 2. Capacity for correction of the epiphyseal line inclination expressed in degrees/month. Means and s.d. are given

	RADIUS		ULNA
	Dorso-volar plane	Radio-ulnar plane	Dorso-volar plane
All observations	0.91 ± 0.57 60 obs. (36 cases)	0.80 ± 0.31 22 obs. (14 cases)	0.82 ± 0.43 10 obs. (7 cases)
Primary angulation 0° - 14°	0.25 ± 0.28 4 obs. (4 cases) (**)	-	-
Primary angulation 5° - 14°	0.75 ± 0.56 30 obs. (18 cases) (***)	0.74 ± 0.28 18 obs. (13 cases)	0.68 ± 0.37 8 obs. (5 cases)
Primary angulation ≥15	1.18 ± 0.47 26 obs. (14 cases)	1.08 ± 0.29 4 obs. (1 cases)	1.36 ± 0.08 2 obs. (2 cases)

The statistical significance of differences between the groups with different primary angulations in the dorso-volar plane of the radius was tested against the group with primary angulations of 5° - 14° and is indicated by asterisks in the table: ** = $0.01 > P > 0.001$, *** = $P < 0.001$.

Table 3. Capacity for correction of the epiphyseal line inclination expressed as β (CPC). Means and s.d. are given

	RADIUS		ULNA
	Dorso-volar plane	Radio-ulnar plane	Dorso-volar plane
All observations	0.087 ± 0.058 60 obs. (36 cases)	0.112 ± 0.041 22 obs. (14 cases)	0.101 ± 0.046 10 obs. (7 cases)
Primary angulation 0° - 4°	0.072 + 0.083 4 obs. (4 cases)	-	-
Primary angulation 5° - 14°	0.095 ± 0.070 30 obs. (18 cases)	0.119 ± 0.037 18 obs. (13 cases)	0.101 ± 0.043 8 obs. (5 cases)
Primary angulation ≥15°	0.074 ± 0.029 26 obs. (14 cases)	0.077 ± 0.041 4 obs. (1 cases)	0.101 ± 0.051 2 obs. (2 cases)

No statistically significant differences were found between the groups with differer primary angulations in the dorso-volar plane of the radius.

Mathematical analysis of the correction capacity. The observations mentioned above suggested that the process followed an exponential course. In order to test this hypothesis the following exponential equation was designed to describe the correction.

$$V_1 = V_0 \exp(-\beta C) \quad \text{where} \quad \beta = \frac{\ln (V_0/V_1)}{C}$$

β = individual correction factor, C = other factors, e.g. time, growth, V_0 = angulation of the epiphyseal plate at the first observation before correction, V_1 = angulation of the epiphyseal plate after correction during the time C.

The exponential expression can be translated into a constant percentage correction (CPC) of the residual angulation.

Example: Calculation of correction to be expected in a case with a 30-degree inclination of the epiphyseal plate after healing of a fracture. Hypothetical value of $\beta = 0.105$, C = 1 month.

$V_1 = 30° \exp(-0.105 \times 1)$ $V_1 = 30° \times 0.90$
$V_1 = 27$; correction = 3° during the first month.

Percentage correction = 10 per cent/month. A correction of 10 per cent a month the residual angulation will give during the following month 2.7° of correction ($V_1 = 27°$ exp (-0.105×1); $V = 24.3°$).

Mean correction expressed as constant percentage correction/month. The mean CPC capacity found at the distal radial epiphyseal plate was 9 per cent/month in the dorso-volar plane and 11 per cent/month in the radio-ulnar plane. A mean value of 11 per cent/month was found for the distal ulnar epiphyseal plate. The corresponding values for β are illustrated in Table 3. An analysis of the CPC capacities in the dorso-volar plane of the radius showed no differences between the groups with different primary angulations.

When all observations were considered, the CPC capacities found at the distal radial epiphyseal plate were similar to those found at the distal ulnar epiphyseal plate. The CPC values for angulations of the distal epiphyseal plate of the radius were 0.082 ± 0.059 (53 obs.) in the dorsal direction, 0.136 ± 0.050 (7 obs.) in the volar direction, 0.105 ± 0.037 (17

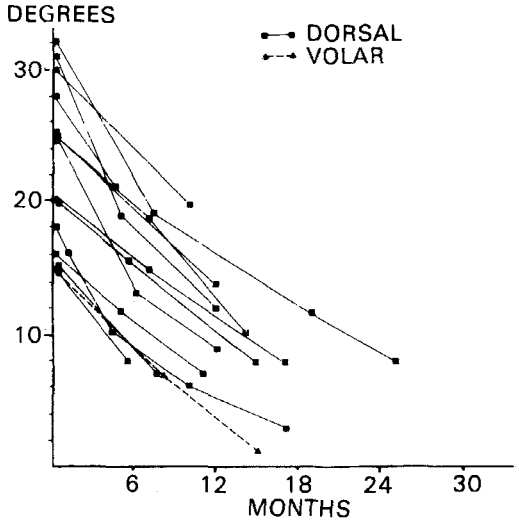

Figure 3. The spontaneous change in inclination of the epiphyseal plates found in the dorso-volar plane of the radius in cases with more than 14 degrees of primary angulation. The different directions of angulation are illustrated.

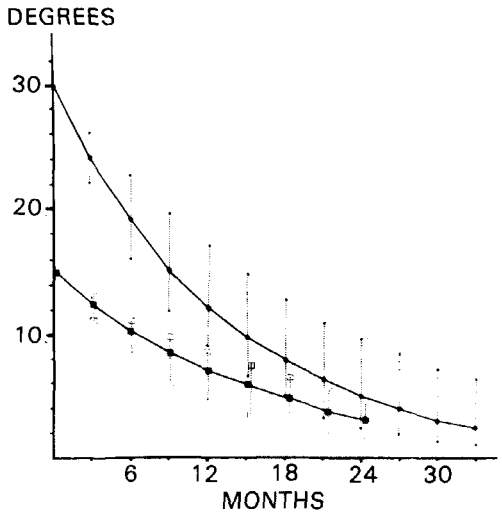

Figure 4. The normalization of the epiphyseal plate in two hypothetical cases with primary angulations of 15 and 30 degrees. The mean value of β found in the lateral view of the radius has been used. $\beta = 0.074 \pm 1 \times s.d. = 0.029$. Mean CPC correction = 6.1 per cent.

obs.) in the radial direction and 0.134 ± 0.049 (5 obs.) in the ulnar direction. These values showed that in the distal radial epiphyseal plate the CPC capacity was lower for angulations in the dorsal direction than for those in the volar and ulnar directions ($P = 0.001$ and 0.03, respectively).

The correction of hypothetical inclinations of 15 and 30 degrees was calculated using the mean value of CPC for primary angulations over 14 degrees in the dorso-volar plane of the radius (Figure 4). These curves are to be compared with the curves from patients with comparable angulations of the epiphyseal plate (Figure 3).

Correlations of different variables with the constant percentage and the linear correction (degrees/month). In the dorso-volar plane of the radius the mean values of the CPC and linear correction (LC) for each patient (36 obs.) were analysed by correlation matrices and stepwise regression analysis. A non-significant correlation was found between the CPC capacity and the primary angulation. In contrast, the LC was highly significantly correlated ($P < 0.001$, corr. coeff. = 0.64) with the primary angulation in the sense that increased primary angulation resulted in higher LC values.

A significant correlation ($0.05 > P > 0.01$, corr. coeff. = 0.35) existed between the CPC capacity and the type of fracture. The CPC capacity decreased slightly from simple torus fractures through greenstick to complete fractures. The correlation between this parameter and the LC was not significant.

No significant correlations existed between age, sex, side, treatment and distance of fracture from the epiphyseal plate and the correction capacities calculated by the two methods.

Prognostic value of constant percentage and linear correction. The mean values for the CPC and the LC found in the dorso-volar plane of the radius were tested for their prognostic value. The expected correction

according to these mean values was calculated for each observation. This expected correction was then compared with the actual correction found in the patients.

The mean absolute deviation for each observation (60) was $2.2° \pm 1.69°$ when the CPC was used. The linear correction values resulted in a higher ($P = 0.003$) mean absolute deviation ($3.6° \pm 4.1°$).

In the same part of the material the means for each individual patient found by the two methods were compared as a prognostic tool in the individual patient. This resulted in a highly significant ($P < 0.001$) increase in prognostic accuracy for both methods when compared with the general prognosis stated above. The absolute mean deviation for the CPC ($0.8° \pm 0.58°$) was also in this prognosis significantly ($P = 0.02$) lower than the values found for the linear correction ($1.4° \pm 1.65°$).

The capacity for correction expressed as a function of longitudinal growth

The rate of correction was expressed in this part of the study as a function of the longitudinal growth produced by the epiphyseal plate, i.e. growth was substituted for time.

The mean CPC capacity and the linear capacity for correction as a function of growth were found to be similar to the corresponding ones found for time. Thus the mean CPC for growth was 9 per cent in the dorso-volar plane and 10 per cent in the radio-ulnar plane of the radius. The ulnar epiphysis showed a correction of 10 per cent. The values found for correction as a function of growth were further tested as prognostic tools in the series. No differences in accuracy were found when these results were compared with those obtained for time.

DISCUSSION

The effect of residual angulation of healed distal forearm fractures in children on the spatial orientation of the distal epiphyseal plates of the radius and ulna was investigated. The general finding was that the epiphyseal plates had a definite spontaneous ability to change their inclinations in relation to the bones of the forearm. Without exception, the change in inclination tended towards a normalization of the inclination of the epiphyseal plate. This is in agreement with the results recently observed in experimental studies (Ryöppy & Karaharju 1974, Karaharju et al. 1976) and with the case report made by Pauwels (1975). The capacity for correction expressed as degrees per month was found to be dependent on the degree of primary angulation after healing of the fracture. Thus, increased angular deviation from the normal position increased the correction capacity. Furthermore, the correction capacity diminished with increasing degrees of normalization. In isolated cases with small primary angulations no change in epiphyseal inclination occurred.

The probable explanation for spontaneous normalization of abnormal inclinations of the epiphyseal plate is an altered distribution of growth within the plate, probably due to a change in the direction and amplitude of the biomechanical forces acting on the plate (Ryöppy & Karaharju 1974, Pauwels 1975). From the results of the present study the following general rules for the behaviour of the process may be deduced. A redistribution of growth in the epiphyseal plate is induced by an abnormal inclination of the plate. An increase in the abnormal inclination will increase the redistribution of growth. Minor changes in inclination do not necessarily result in a redistribution of growth. Once started the process strives to restore a normal orientation of the epiphyseal plate.

The highly significant correlations found between the capacity for angular correction expressed as degrees per month and the amount of primary angulation of the epiphyseal plate strongly indicated that the correction process was not linear with time. Instead, the general behaviour of the process suggested an exponential dependence, i.e. a constant percentage correction (CPC). Such a

dependence can also be traced from the experiments performed by Karaharju et al. (1976). To test this hypothesis, an exponential model equation was designed to express the course of the process. When the model equation was used, the dependence on the primary angulation disappeared. To further investigate whether the CPC was a more accurate method for describing the correction than the linear term, degrees per month, the mean values for the parameters were used as prognostic tools in the series. The result was that the use of CPC produced a marked increase in prognostic accuracy compared with linear correction. This proved that the general course of the process of correction was more accurately described by an exponential than by a linear expression.

The mean values for the correction of abnormal inclinations of the epiphyseal line found in this study permit an evaluation of the rate of correction to be expected in the individual case. A further increase in the accuracy of the estimation of the correction to be expected in a specific case will ensue if a CPC value for the individual is obtained. The possibility of calculating the correction to be expected opens a way for early detection of growth disturbances due to epiphyseal damage.

It is also possible to calculate the approximate time needed for adequate correction of the inclination of the epiphyseal plate or, in other words, adequate correction of the inclination of the joint plane. The latter possibility is of decisive importance, especially in adolescent patients in whom epiphyseal closure will occur within a few years. The present results suggest, but have not proved, that full correction will, in fact, occur. Theoretically, the exponential equation implies that full correction cannot be reached. In clinical practice the calculation of the time needed for correction must therefore be performed for adequate correction, e.g. 2 degrees of remaining angulation. This assumption will give the following formula for the time in months (t) for adequate correction (2°):

$$t = \frac{\ln (V_o/2)}{\beta}.$$

No significant correlations were found between the correction capacity and the age at the time of the fracture. At first sight, this result is not in agreement with the general opinion that the capacity for remodelling of the fracture site is more pronounced in the younger age groups (Önne & Sandblom 1949, Blount 1955, 1967, Miyagi & Murayama 1964, Sharrard 1971, Ryöppy 1972). This discrepancy can be explained by the fact that in earlier reports remodelling at the site of the fracture – not the correction of the epiphyseal plate – has been studied. Provided that a normalization of the inclination of the epiphyseal plate occurs, an automatic reduction of the angulation at the fracture site must follow due to the lengthwise growth produced by the plate. This automatic reduction in angulation will then be more pronounced in a younger child.

In the present series of fractures in the distal fifth of the bones no differences in the rate of correction of the epiphyseal plate were found in fractures located at different distances from the plate. It is possible that the relatively small differences in distance were insufficient to produce any detectable changes in the capacity for correction. The prevailing opinion expressed in the literature is that the capacity for remodelling at the fracture site decreases with increasing distance between the fracture and the epiphyseal plate (Önne & Sandblom 1949, Blount 1955, 1967, Sharrard 1971, Ryöppy 1972). However, the present results are compatible with the observations made at the fracture site as the growth in length produced by the epiphyseal plate will automatically reduce any angulation of the bone. This reduction in total angulation of the bone will then of necessity be more pronounced the closer the fracture is located to the epiphyseal line.

No previous study has been published in

which the remodelling capacity of different bones can be compared directly. In the present study the radial and ulnar epiphyseal plates had similar capacities for correction. This similarity might be due to the location of the structures in the same anatomical area and must not be interpreted to mean that other epiphyseal plates with different anatomical locations will necessarily have a similar rate of correction. At the distal radial epiphyseal plate volar and ulnar angulations resulted in a higher rate of correction than angulations in a dorsal direction. This indicates that local factors pertaining to a specific epiphyseal plate are capable of influencing the correction capacity. Comparable results have been found in tibial fractures where angulations in the antero-posterior plane are known to have a better capacity for remodelling than angulations in the tibiofibular plane (Blount 1955, 1967, Bennek & Steinert 1966, Spissak et al. 1969, Sharrard 1971).

The process of correction must be attributed to a reorientation of growth at the epiphyseal plate. Consequently, there was the possibility that the amount of longitudinal growth produced by the epiphyseal plates would give a more exact picture of the correction capacity. However, no major differences were found between the correction expressed as a function of time and as a function of growth. These results support the observation that longitudinal growth of long bones has a comparatively linear relationship with time (Andersson et al. 1963, 1964, Diethelm 1968, Hedström 1969).

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