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Quantitative assessment of callus distraction using dual energy X-ray absorptiometry

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Summary. *Bone mineralisation during and after limb lengthening procedures on the femur or tibia using unilateral fixators has been monitored quantitatively using dual energy X-ray absorptiometry (DEXA). We measured the bone mineral density (BMD) prospectively in the newly formed callus, in the bone adjacent to the callus and in the proximal femur. In twenty-one patients we showed a typical course with a peak value at 4–6 weeks after beginning distraction and a minimum value at maximum distraction. In the consolidation period the BMD in the distraction gap increased until the fixator was removed. The BMD in the regenerated bone increased faster in the regions of interest (ROI) opposite the fixator compared to those near it. Dynamisation caused more homogeneous regeneration equalising V_{BMD} in the different ROIs. The BMD in the proximal femur of the leg which was operated on decreased to 67% and in the opposite leg to 87% of the preoperative value. DEXA provides a precise and quantitative assessment of callus and bone mineralisation during limb lengthening and helps in understanding what is happening during these procedures.*

Résumé. *Le processus de la minéralisation peut précisément être étudié d'une manière quantitative pendant et après la distraction du cal au moyen de l'absorptiométrie en énergie-binaire (DEXA) en créant une petite radioexposition. Des patients (n = 21) avec une distraction du cal, auxquels nous avons mesuré prospectivement la densité minérale de l'os (bone mineral density = BMD) dans et autour du cal nouvellement formé, étaient traités avec des fixateurs externes unilatéraux. La minéralisation a montré une courbe typique avec une première pointe de valeur [0,365 +/– 0,196 g/cm² (30,9% de la première valeur)] à 4–6 semaines après le début de la distraction. Une valeur minimale apparut à la distraction maximale. Dans la période de consolidation la BMD est montèe jusqu'au moment de l'enlèvement du fixateur à 1,020 +/– 0,234 g/cm² (87%). La minéralisation du cal, mésurée grâce à la technique des «regions of interest (ROIs)», augmenté plus vite aux ROIs éloignées qu'aux ROIs très proches du fixateur. De la dynamisation du fixateur résulte une vitesse de minéralisation plus homogène. Nous considérons la DEXA comme une méthode précise pour étudier les processus de la minéralisation et du développement du cal pendant la distraction avec un fixateur unilatéral. En tenant compte des limites de la technique, la DEXA – qui nous livre des valeurs quantitatives – nous aide à comprendre ce qui se passe pendant la distraction.*

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Introduction

Clinical observation and radiographs are the standard methods of investigating distraction procedures using unilateral fixators. This involves relatively high exposure to radiation, the delayed appreciation of callus and poor quality radiographs, especially when large films are used [11, 12]. Sonography [7, 9, 17] and osteodensitometry [5, 6] have been used to calculate the quality of the callus.

Table 1. Course of mineralization (BMD) of ROI 2–4 of the callus during the period of distraction and the post distraction or callus regeneration period

Distraction period: time after operation	2 weeks	4 weeks	6 weeks	8 weeks	10 weeks
ROI 2 (callus opposite the fixator	0.048 ± 0.128	0.317 ± 0.333	0.303 ± 0.208	0	0.053 ± 0.130
ROI 3 (centre of the callus)	0	0.259 ± 0.219	0.289 ± 0.228	0	0.093 ± 0.146
ROI 4 (callus near the fixator)	0.034 ± 0.089	0.197 ± 0.203	0.169 ± 0.171	0	0.047 ± 0.166
Callus regeneration period: time/ROI	End of distraction	4 weeks after distraction	4 weeks to fixator removal	Fixator removal	4 weeks after fixator removal
ROI 2 (callus opposite the fixator)	0.194 ± 0.176	0.445 ± 0.292	0.802 ± 0.274	0.971 ± 0.369	1.002 ± 0.388
ROI 3 (centre of the callus)	0.183 ± 0.197	0.504 ± 0.268	0.876 ± 0.203	1.105 ± 0.271	1.230 ± 0.369
ROI 4 (callus near the fixator)	0.113 ± 0.137	0.294 ± 0.164	0.616 ± 0.163	0.837 ± 0.240	0.949 ± 0.257

The advantages of dual energy X-ray absorptiometry (DEXA), which is usually used for the diagnosis and observation of treatment of osteoporosis, are the low radiation exposure (1 μSv per scan, [8]) and the opportunity to assess the mineralisation of the callus quantitatively.

In this prospective study, we have investigated the normal course of mineralisation of the callus, and of the bone adjacent to it, in patients who were undergoing unilateral lengthening with unilateral fixators. We developed a standard scheme to discover whether DEXA is useful in analysing the mineralisation of callus and the bone adjacent to it.

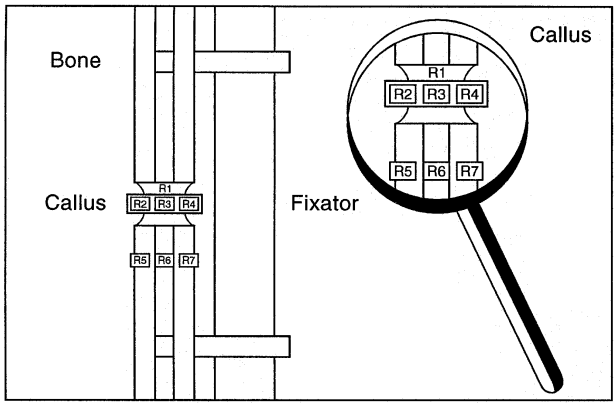

Fig. 1. Scheme for analysis of callus (ROI 1–4) and the bone adjacent to the callus (ROI 5–7)

Patients and methods

We investigated 21 patients chosen from our outpatient clinic, who underwent leg-lengthening procedures using the Heidelberg external fixation system (Zimmer Chirurgie, Dietzenbach, Germany). There were 10 females and 11 males, with an average age of 17 ± 6 years, height 1.61 m ± 0.18 and weight 57 ± 17 kg. Only patients with an uncomplicated and correct course of distraction were selected. The patients and their parents were informed about the aims of the study and the investigations.

A minimally invasive percutaneous osteotomy was carried out [13] and distraction begun one week later at 1 mm per day divided into 4 steps of 0.25 mm. Full weightbearing was allowed from the first day [15]. As soon as both bony cortices were seen, dynamisation of the fixator was performed [14]. The femur was distracted in 11 patients, the tibia in 7 and a combined distraction in 3 with distraction of both lower limbs, bisegmental distraction and cross-leg distraction. The length of distraction was 5.3 ± 2.1 cm on average and the fixator was removed after 27 ± 10 weeks.

Table 2. Course of mineralization (BMD) of the bone adjacent to the callus (ROI 5–7)

Time/ROI	Post operation	End of distraction	4 weeks after distraction	4 weeks to fixator removal	Fixator removal	4 weeks after fixator removal
ROI 5 (cortex opposite the fixator)	1.351 ± 0.497	1.180 ± 0.370	1.099 ± 0.380	1.108 ± 0.363	1.096 ± 0.443	1.161 ± 0.456
ROI 6 (cancellous bone)	1.121 ± 0.369	1.007 ± 0.365	0.965 ± 0.356	0.893 ± 0.339	0.918 ± 0.362	0.927 ± 0.321
ROI 7 (cortex near the fixator)	1.205 ± 0.396	1.089 ± 0.252	1.065 ± 0.381	0.970 ± 0.373	0.985 ± 0.305	1.066 ± 0.386

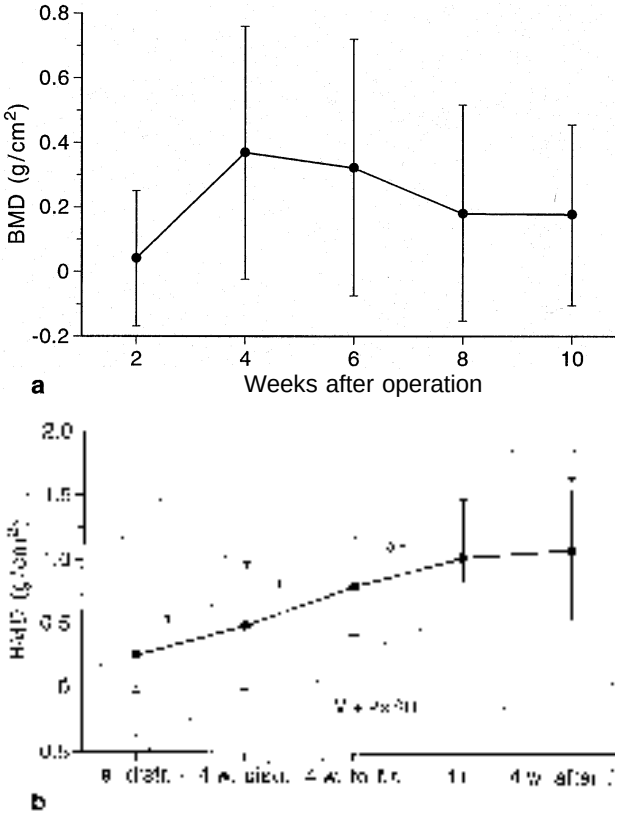

Fig. 2. a The course of mineralisation (BMD) of callus (ROI 1) during distraction. **b** The course of mineralisation (BMD) of callus (ROI 1) after distraction (the callus regeneration period). Results of statistical testing (paired Student's *t*-test * = $P < 0.05$; ** = $P < 0.01$). *e. distr.*, end of distraction; *4w. distr., 4 weeks after the end of distraction; 4w. to f. r.,* 4 weeks to fixator removal; *f. r.,* fixator removal; *4w. after f. r.,* 4 weeks after fixator removal

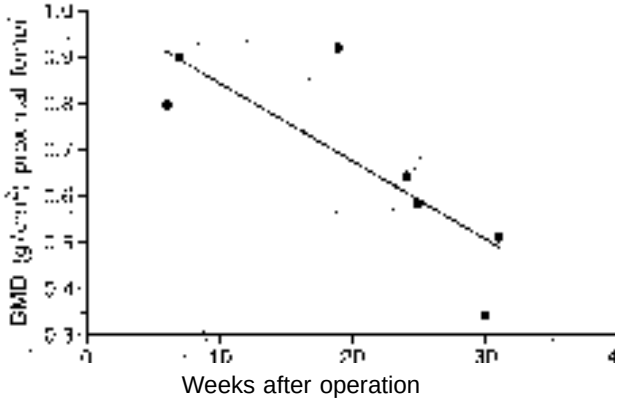

Fig. 3. Statistically significant negative correlation (Pearson's coefficient, $r = -0.809$; $P < 0.05$) between the time the fixator was in use and the BMD of the proximal femur of the operated leg

Technique

Scans were performed with a second generation dual energy X-ray absorptiometer (QDR 2000, Hologic). The results are shown as an area density in g/cm². We defined 7 reproducible ROIs: ROI 1–4 covers the callus and ROI 5–7 the bone adjacent to the callus (Fig. 1). Measurements of the proximal femur were carried out before operation and after 6 months using the preinstalled standard interactive software (Hologic) to analyse the BMD of the neck and proximal femur.

Timetable

The patients were scanned once during the first 3 days after operation, every 2 weeks during distraction, once at the end of distraction period, once four weeks after distraction period, once 4 weeks before the fixator was removed, once at the time of its removal and once 4 weeks after. All fixators were dynamised at 4 weeks.

Table 3. Mineralization velocity (V_{BMD} [(g/cm²)/w]) of the different ROI of the callus. The dynamization of the fixator has a different effect on the V_{BMD} of the different ROI of the callus.The V_{BMD} decreases at the callus near the fixator (ROI 2) and at the centre of the callus (ROI 3). It increases at the callus near the fixator (ROI 4)

Period/ ROI	'End of distraction' to '4 weeks to fixator removal'	'4 weeks to fixator removal' to 'fixator removal'
ROI 2	0.054 ± 0.048	0.041 ± 0.030
ROI 3	0.062 ± 0.052	0.058 ± 0.050
ROI 4	0.040 ± 0.029	0.057 ± 0.039

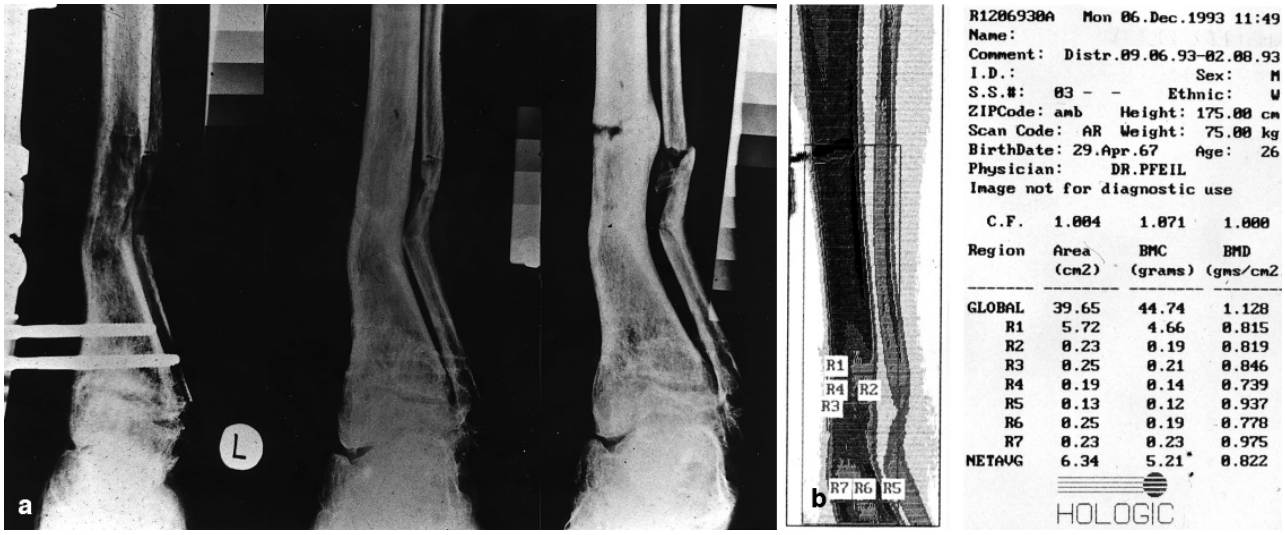

Fig. 4. a Conventional radiographs of a patient, 26 years of age, at the time of fixator removal and 2 weeks later. Fracture of the callus occurred 2 weeks after the fixator was removed, although the radiographs showed normal mineralisation. **b** The original DEXA measurement when the fixator was removed. The BMD of the callus in ROI 1 was only 80% (ROI 1 = 0815 g/cm² of our normogram (1.020 ± 0.234 g/cm²)

Quality control

An anthropometric spine phantom (#1179, Hologic) was used for daily control.

Statistical methods

Normal distribution was tested by the Kolmgorov-Smirnov-Test. The following results are shown as mean (M) $\pm$ standard deviation (SD), in figures as M ± 2*SD. The paired Student's *t*-test was used to test the difference in two distributions. We could not use the repeated measures ANOVA because not all the patients were available at every time of measurement.

Results

BMD of the callus (distraction period)

Two weeks after operation the callus in ROI 1 showed the first evidence of mineralisation (Fig. 2 a). At 4 weeks the BMD increased in value and then decreased until the end of distraction. There was no significant difference when testing the distributions. The BMD near the fixator (ROI 4) showed a similar profile and was always lower than the BMD in the callus opposite the fixator (ROI 2) (Table 1).

BMD of the callus post distraction period

We saw a steady increase in BMD in all ROIs (1–4) of the callus (Table 1), (Fig. 2 b). The BMD at the removal of the fixator reached 87% of the first postoperative measurement of the callus (ROI 1), 72% in the callus opposite the fixator (ROI 2), 98% in the centre of the callus (ROI 3) and 69% near the fixator (ROI 4) (Table 1).

Dynamisation of the fixator

The mineralisation velocity (V_{BMD}), shown as the change of BMD per week (g/cm²)/w), was defined and calculated for the different ROIs of the callus. Only the callus near the fixator in ROI 4, which had the lowest BMD at every period before dynamisation, showed a statistically significant in-

crease ($P < 0.05$) in V_{BMD} by 43%. The V_{BMD} in ROI 2 near the fixator and in the centre of the callus decreased (Table 3).

BMD of bone adjacent to the callus

This decreased until 4 weeks after distraction in the cortex opposite the fixator (ROI 5), or 4 weeks before fixator removal in cancellous bone (ROI 6) and in the cortex near the fixator (ROI 7). After this, the BMD of all ROIs increased again to 81% (ROI 5) or 82% (ROI 6 and 7). Four weeks after removal of the fixator, the BMD remained lower than it was before operation (Table 2).

BMD of the proximal femur

At the time of fixator removal (20 ± 6 weeks), the mineralisation at the side of distraction (0.667 ± 0.214 g/cm^2) was only 76% of the BMD of the proximal femur opposite to the fixator (0.874 ± 0.165 g/cm^2) in 7 patients. The correlation between the BMD on the operated leg and the time the fixator was in use was statistically significant (Pearson's correlation coefficient, $r = 0.809$, $P < 0.05$) (Fig. 3). There was a negative correlation ($r = 0.544$, $p > 0.05$) at the proximal femur of the opposite side which was without statistical significance ($P > 0.05$).

Case report

A man, 26 years of age, had a fracture of the callus 2 weeks after removal of the fixator as shown by conventional radiographs (Fig. 4a). Retrospective analysis of the DEXA measurement when the fixator was removed showed his BMD was only 80% (ROI 1, 0.815 g/cm^2) of our reference value (Fig. 4b), which is the mean (Fig. 2b) of our patients with a normal course of distraction.

Discussion

DEXA permits noninvasive and quantitative measurement of the course of mineralisation in callus during distraction procedures. Resolution of 1 mm/pixel was enough to distinguish the distraction gap from bone. Although the width of the scan (26.5 cm) covered the fixator screws on both sides of the osteotomy, it was impossible to assess the axis of the operated leg correctly. If the scan were wide enough to assess the axis, and used together with other methods such as ultrasound, it should be possible to reduce the number of radiographs taken during distraction.

We saw the first mineralisation of callus 2 weeks after operation, and in all ROI the BMD showed a typical course with a peak at 4 to 6 weeks. With further distraction the BMD reached minimal values as previously reported [3]. During the period of distraction the BMD of the callus opposite the fixator was always higher than the BMD near it. This is caused by the elasticity of the fixator [3] since the stress of walking leads to a higher vibration amplitude opposite the device and asymmetric stimulation of mineralisation. A similar pattern of mineralisation using unilateral fixators, compared with the Ilizarov ring showing a more homogeneous mineralisation, is known from clinical observations [1].

The increase of BMD in callus after distraction, or when callus is regenerating, can be measured quantitatively using DEXA, but during our study the indication for removal of the fixator was judged clinically and by radiographs. At removal, mineralisation was 87% of the preoperative value, higher than that reported by Eyres et al. (74%) who compared the callus BMD to a ROI in the opposite leg at the time of distraction [5]. This may be because the BMD of the opposite leg decreases in a different way from that of the operated leg as the patient's activities are reduced. The time of fixator removal should depend on the lowest BMD value which is 69% for the callus near the fixator (ROI4) in our cases.

The course of distraction in this study can be represented as a normogram, patients with an uncomplicated course being included within this. Mineralisation in other patients can be compared, and can be assessed in every case qualitatively and quantitatively so that the distraction rate and removal of the fixator can be determined more exactly. By this means the fracture which occurred in one of our patients might have been prevented. At the end of the callus regeneration period (from about 0.600 g/cm^2), the BMD should be measured every 2 weeks to find the correct time to remove the fixator.

The effect of dynamisation of the fixator can be shown quantitatively by comparing the different ROIs, which showed that dynamisation led to an equalisation of BMD in different parts of the callus and more homogeneous callus mineralisation.

The procedure of callus distraction is associated with decreased activity of the patient, as indicated by the decrease in BMD to 87% in the proximal femur of the opposite leg. The patients were advised to bear full weight on their operated leg, but the BMD in the proximal femur decreased to 67%, which correlated negatively with the duration of distraction. In the bone adjacent to the callus, the BMD first decreased until 4 weeks after distrac-

tion, and then increased to 92% 4 weeks after the fixator was removed when weightbearing was also increased. Other reasons for bone loss adjacent to the callus could be damage to vessels in the bone by the osteotomy [4], or a higher bone turnover after fracture [16].

This technique of measurement with DEXA describes mineralisation which is only one factor in bone quality, beside the organic synthesis and microarchitecture of bone. It is, however, an important factor in assessing the stability of bone since stiffness and torsion are closely related to BMD [2, 10]. Nevertheless DEXA, together with a scheme for standard analysis and a normogram, may help in determining management of the distraction process and so reduce possible complications.

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