Negative correlation between extent of physeal ablation after percutaneous permanent physiodesis and postoperative growth

Volume computer tomography and radiostereometric analysis of 37 physes in 27 patients

Ragnhild B Gunderson[1], Joachim Horn[2], Thomas Kibsgård[2], Leif Pål Kristiansen[2], Are Hugo Pripp[3], and Harald Steen[2,4]

Departments of [1]Radiology and [2]Orthopaedics; [3]Biostatistics and Epidemiology Unit; [4]Biomechanics Laboratory, Rikshospitalet, Oslo University Hospital, Oslo, Norway.
Correspondence: ragnhild.gunderson@ous-hf.no
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Background and purpose **Percutaneous physiodesis in the knee region is a well-established method for treating leg-length inequality. Longitudinal growth in the physis is believed to stop almost immediately after the operation. The extent of physis ablation required has never been investigated by any kind of tomography in humans. Using radiostereometric analysis (RSA), we determined when definite growth arrest occurred after surgery. We also studied the correlation between the extent of physis ablation and postoperative growth. Finally, we assessed any bone bridging across the physis.**

Methods **6, 12, and 30 weeks after surgery, we used RSA to measure longitudinal growth in 27 patients (37 physes) with a mean age of 13 years. CT scanning of the knee region was performed 12 weeks after surgery to measure the percentage of the ablated physis and to determine the distribution of bone bridges across the physis.**

Results **RSA showed that growth rate was reduced to less than half of the expected rate after 6 weeks. During the next 6 weeks, the growth ceased completely. CT scans revealed a large variation in the extent of ablated physes (17–69%). In the ablated areas, tissues of various densities were mixed with mature bone. Bridges were found both laterally and medially across the physes in all of the patients. There was a negative correlation between the extent of ablation and total postoperative growth (rho = –0.37, p = 0.03).**

Interpretation **Growth across the physis is effectively stopped by percutaneous physiodesis. RSA is well-suited for observation of this phenomenon. Volume CT scanning can be used to detect bone bridges that cross the physis and to calculate the extent of physis ablation.**

Percutaneous physiodesis is a well-established method for treating leg-length inequality (LLI) (Bowen and Johnson 1984, Canale et al. 1986). In general, indication for surgery is LLI of 2–5 cm (Steen et al. 1997). If LLI is more than 5 cm, bone elongation should be considered. Complications are rare (Inan et al. 2008); however, failure to achieve fusion may occur (Scott et al. 1996, Edmonds and Stasikelis 2007). The timing of the operation is based on the patient's skeletal age and the degree of anisomelia. The aim is to obtain identical leg lengths at maturity. It is believed that longitudinal growth in the physis stops almost immediately after the operation. In their RSA-based study of 10 patients, Lauge-Pedersen et al. (2006) reported small increases in longitudinal length across the distal physis of the femur for up to 3 months postoperatively. According to Timperlake et al. (1991), 4–6 months is required for bone bridges to form across the growth plate after percutaneous physiodesis. However, this conclusion was based on standard radiographs.

Our aims were to determine when definite growth arrest occurs after percutaneous physiodesis in the knee region and to study the relationship between the extent of physis ablation and the degree of postoperative growth.

Patients and methods

29 patients underwent permanent percutaneous physiodesis in our hospital between June 2009 and June 2011. 2 patients were excluded, 1 because of inadequate placement of the implanted tantalum spheres required for RSA and the second because of

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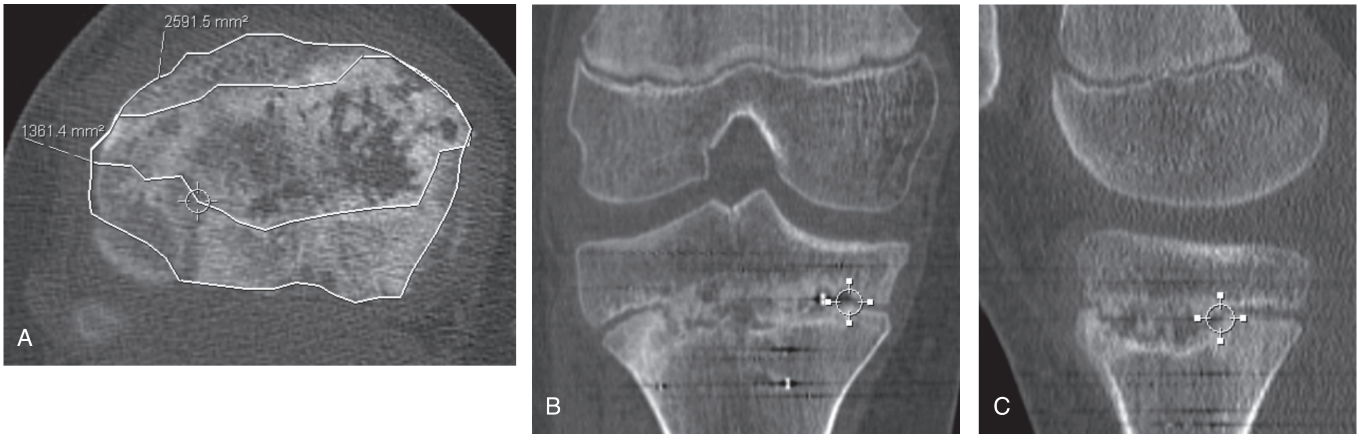

Figure 1. CT-scan reconstructions 3 months after tibial physiodesis in a 12-year-old boy (right leg). A. CT axial reconstruction. B. CT coronal reconstruction. C. CT sagittal reconstruction.

loss to follow-up. None of the patients underwent surgery on both legs, but 10 patients had unilateral combined physiodesis performed both on the distal femur and the proximal tibia. Thus, we included 37 surgeries in 27 patients (18 boys), 15 in the femur and 22 in the tibia. Mean age at the time of surgery was 13.3 (10.3–15.8) years. The mean age for girls was 12.1 (10.3–14.1) years and the mean age for boys was 14.0 (12.1–15.8) years. At operation, there was a mean LLI of 32 (15–70) mm. 2 children with LLI of 60 and 70 mm were treated with physiodesis on the long leg and were planned for a later elongation procedure for the opposite, short leg. The LLIs were attributed to the following causes: congenital disorders (n = 16), previous infections (n = 3), growth disturbances resulting from juvenile idiopathic arthritis (n = 3), and idiopathic anisomelia (n = 5). Patients with combined axial deviation and LLI were not included.

Percutaneous physiodesis was performed by a modified technique based on the originally described methods of Bowen and Johnson (1984) and Canale et al. (1986). A 1-cm skin incision was made laterally and medially over the proximal tibial physis and/or distal femoral physis. Under image intensification, an awl was advanced 1.5 cm into the physeal plate followed by a 6-mm power-drill bit. The peripheral 1.5- to 2-cm part of the physis was first ablated by fan-shaped oscillating drilling and then further ablated by a 3-mm curved curette. Toward the end of the operation, 4–6 tantalum spheres measuring 0.8 mm in diameter were inserted into the bone throughout the cross-sectional area both proximal and distal to the physis.

RSA of the knee was performed within 1 day of surgery. A specially designed calibration cage for knees was used (Standard Bi-planar cage no. 10; RSA BioMedical, Umeå, Sweden). The patient sat with the leg stretched out inside the cage with the knee placed in the center. 2 X-ray phosphorous screens (corresponding to the films) were mounted, below and behind the cage, respectively. 2 ceiling-mounted X-ray tubes were positioned at 90° angles to each other and fired simultaneously. The X-rays were sent to the PACS, and then electronically to the RSA program (UmRSA Analysis version 6.0). Using the RSA software, growth across the physis was calculated as the change in the distance across the physis between 2 examinations.

The RSA procedure was repeated after 6, 12, and 30 weeks. 2 patients missed the last examination. All analyses were performed by the same experienced radiologist (RBG).

At 12 postoperative weeks, we performed a CT scan (16-row detector) of the knee. All exposures were volume scans with a slice thickness of 0.625 mm, and they were reconstructed to 1.20 mm in the axial (transversal), sagittal, and coronal planes. The CT slice found by RBG to be in the center of the physis was used for analysis to differentiate intact and ablated physes. Intact and ablated regions could easily be defined on axial CT images, but not without the aid of a simultaneous localizer in the sagittal and coronal planes (Figure 1). PACS software was also used to estimate the relevant areas traced in mm^2. The proportion of each tissue type (intact or ablated physis) was calculated as a percentage of the total cross-sectional physeal area in the chosen CT slice. Repeated measurements for intra-observer analysis were performed at 3-week intervals for all physes. To determine the level of inter-rater reliability, a random sample of image measurements from 19 physes was conducted by 2 researchers (RBG and a resident in radiology). In addition, the occurrence of solid bone bridges crossing the physis in the ablated areas was visually estimated.

The RSA measurements were performed according to the "Guidelines for standardization of radiostereometry (RSA) of implants" (Valstar et al. 2005). The accuracy of the RSA laboratory measurements was evaluated in a phantom experiment, and there was no bias for which correction was needed. The precision was evaluated with repeated examinations performed on 8 physes, with the patient, the cage, and the X-ray

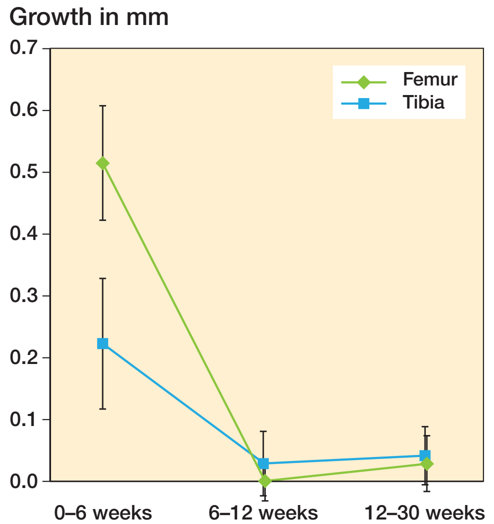

Figure 2. Growth in the femur and the tibia. Mean values with 95% CIs. During the first 6 weeks after surgery, growth was significantly different from zero ($p < 0.001$), and the growth rate was greater in the femur than in the tibia ($p < 0.001$).

tubes relocated between each examination. Precision was calculated as $\pm\, t_{(n\,-\,1)\;0.005} \times SD_{\text{difference between double examinations}}$ (Digas et al. 2003). These double examinations revealed a precision in our RSA system of 0.05 mm, indicating that a measured difference between 2 examinations greater than this value should be interpreted as a real change.

Statistics

Central values were expressed as the arithmetic mean, and dispersion was expressed as the range. Because 20 of the operated physes belonged to 10 patients and because the postoperative growth was measured on 3 occasions, not all of the observations were independent, and the statistical analysis was performed using a mixed model with a random intercept that accounts for the repeated and clustered data structure (PASW version 18; IBM Corporation, Armonk, New York). The statistical model estimated the mean growth with 95% confidence interval (CI). We used Spearman's coefficient for the correlations, and any p-value of < 0.05 was considered statistically significant.

Ethics

This project was evaluated and approved by the Regional Ethics Committee of Norway (REK S-09377b 2009-8352), and each patient and the parents provided written consent to be included in the study.

Results

The longitudinal growth was more than zero across the physes in both the femurs ($p < 0.001$) and the tibias ($p < 0.001$) during the first 6-week postoperative period. The femurs had a mean growth of 0.52 mm, which was significantly greater than the mean growth of 0.20 mm in the tibias ($p < 0.001$) (Figure 2). The greatest growth measurement, which was observed at 6 weeks, was 0.86 mm. The average growth rate during this period was 0.08 mm per week for the femurs and 0.03 mm per week for the tibias (Table 1).

For the last 2 observation periods (6–12 and 12–30 weeks), there were no statistically significant differences in growth between the femurs and tibias or between the time points. The average total growth, combining the femoral and tibial measurements, for these later observation periods was 0.03 mm (CI: 0.00–0.06, $p = 0.05$).

The total growth across the physis for the entire observation period was 0.38 mm on average, with a maximum value of 1.00 mm. There was a negative correlation between the amount of growth and the extent of ablation (Spearman's correlation coefficient rho = –0.37; $p = 0.03$).

The RSA study showed that no angular deformity developed in any patient postoperatively.

The CT images taken 12 weeks postoperatively showed that the area of physis ablation varied from 347 mm^2 to 2,575 mm^2, which corresponded to 17–69% of the total axial area of the physis, with a mean of 35% (Table 2). Thus, on average, an open or intact physis was found in 65% of all axial CT slice areas. The mean ablated part was similar in the tibia (38% (26–55)) and in the femur 32% (17–69) ($p = 0.09$). The appearance of these ablated areas varied in the CT images. In some areas, the density was as great as that of solid bone. In other areas, the tissue densities were lower and compatible with debris, old hematomas or fatty material, such as bone marrow. These

Table 1. Weekly growth in different time periods. Mean (range) in mm

	0–6 weeks	6–12 weeks	12–30 weeks
Mean	0.051 (–0.012 to 0.143) [a]	0.002 (–0.021 to 0.051)	0.002 (–0.010 to 0.012)
Femur	0.079 (0.032 to 0.143) [b]	0.001 (–0.011 to 0.026)	0.001 (–0.007 to 0.006)
Tibia	0.031 (–0.012 to 0.110)	0.004 (–0.021 to 0.051)	0.002 (–0.010 to 0.012)

[a] Total growth at 0–6 weeks was significantly greater than zero ($p < 0.001$).
[b] Femoral and tibial growth at 0–6 weeks were significantly greater then zero, and femoral growth was significantly greater than tibial growth ($p < 0.001$).

Table 2. Distribution (%) of ablated (various tissues) and open (intact) physes found in a cross-sectional area CT analysis 12 weeks postoperatively. Mean (95% CI)

	Ablated physes	Open physes
Total	35 (32–39)	65
Femur	32 (24–39)	68
Tibia	38 (35–40)	62

areas were mixed with components that appeared similar to newly formed bone. All patients had at least 1 continuous confluencing bone-bridging area. This area was located centrally in all patients, except for 8 who had 2 separate small areas of bony healing laterally and medially in the femur.

The inter- and intra-observer analyses for detecting ablated areas on the CT images revealed an intra-rater reliability of 0.98 and an inter-rater reliability of 0.94.

Discussion

By using RSA, we found that longitudinal growth across a physis after surgical physiodesis was severely reduced or stopped in almost all patients within the first 6 weeks after physiodesis in the knee region. The total growth calculated, combining femoral and tibial measurements, after the first 6 weeks was 0.03 mm, which is less than the precision limit of measurements performed with the clinical setup in our lab.

Lauge-Pedersen et al. (2006) reported a study of 10 children who underwent 23 epiphysiodeses. All tibias underwent growth arrest after the first 6 weeks and all femurs underwent growth arrest within 12 weeks, except for 1 patient who experienced failure in 3 of 4 physes.

According to Menelaus (1966), the average normal longitudinal growth rate for adolescent children is 10 mm per year for the distal femur and 6 mm per year for the proximal tibia. These rates correspond to a mean femoral growth rate of 1.15 mm per 6 weeks and a mean tibial growth rate of 0.69 mm per 6 weeks, which is equivalent to 0.19 mm per week and 0.12 mm per week, respectively. Thus, our results indicate that the average growth rate was reduced to less than half the normal rate during the first observation period. Lauge-Pedersen et al. presented their results as weekly longitudinal growth. To compare the results, we also calculated the individual weekly growth rate in our study (Table 1).

According to Lauge-Pedersen's tables, it appears that the growth rate in their study was approximately the same as that in our study during the first 6 weeks. However, they reported some femoral growth thereafter that we could not confirm. Our modified surgical combined technique of the percutaneous methods originally described by Bowen and Johnson (1984) and Canale et al. (1986) included use of a 6-mm diameter oscillating power drill followed by a curved curette. Lauge-Pedersen et al. used an 8-mm cannulated drill without curettage. We do not consider that these small technical differences would have had any major effect on the results.

We did not find that the patient's age, sex, or diagnosis had any influence on postoperative growth in either of the 2 cohorts.

The measurement inaccuracy in our RSA system was calculated by performing RSA phantom studies and repeated examinations, which showed a high degree of precision; changes of > 0.05 mm should be interpreted as real differences. Each repeated examination was performed on the same child twice, with only a few minutes between the examinations. Furthermore, we compared images taken at intervals of 6 weeks or more, and most patients experienced changes of > 0.05 mm, with a maximum growth of ≤ 1 mm for the complete observation period of 30 weeks. However, these values were far less than expected from normal growth and they were considered to be of no clinical relevance.

The reconstructed CT scans were analyzed to determine the extent of ablation of the involved physis and the formation of bone bridges. When viewing only ordinary axial CT slices, we found it difficult to define the extent of physis ablation exactly. Volume CT scanning generates reconstructed images in all 3 planes, and when analyzed using the software available in our PACS, these images could be used to easily differentiate between bone bridges or otherwise ablated physes and intact physes in the trans-sectional area. We found bone bridges in all of the patients. This result was in accordance with our RSA results of no growth after 12 postoperative weeks.

We are not aware of any studies that have shown how much of the physeal area has to be destroyed to result in growth arrest in humans. Benyi et al. (2010) reported removal of between 25% and 50% of the growth plate, but they did not provide further documentation. In a rabbit study, Mäkelä et al. (1988) found that destruction of 7% of the distal femoral physis was sufficient to obtain bar formation and growth arrest. In our CT study, the area of ablation was found to be between 17% and 69% of the axial physeal cross-sectional area. In previous studies, the extent of bone bridging has been determined by radiographs in 2 planes. We also had such radiographs, which were used for RSA. In spite of the low radiation dose, they still showed the physis well (Figure 3). In general, the frontal (AP) exposures suggested a smaller quantity of crossing bone than the laterals. Our CT images demonstrated that ablated areas contained various types of tissue, with densities consistent with old hematomas, debris, fatty components, and fragments of immature bone (Figure 1). In the present example, 53% of the physis was ablated, but the X-rays may suggest less ablation. Unfortunately, it was difficult to define exactly how much of the ablated physeal area was replaced by bone at 12 weeks.

To prevent asymmetric physeal growth after physiodesis, it is necessary to achieve a symmetrical distribution of bone bridges across the physis. The CT examination showed that we successfully achieved this symmetrical distribution. We found symmetric bone bridging centrally or in both the medial and lateral condylar regions in all cases. The distribution was also symmetric in the sagittal plane. This is in accordance with our most important finding of no growth across the physis later than 6 weeks postoperatively.

RBG, HS, LPK, and JH conceived the study. RBG performed all the radiological work and also wrote the manuscript. LPK and JH both performed the

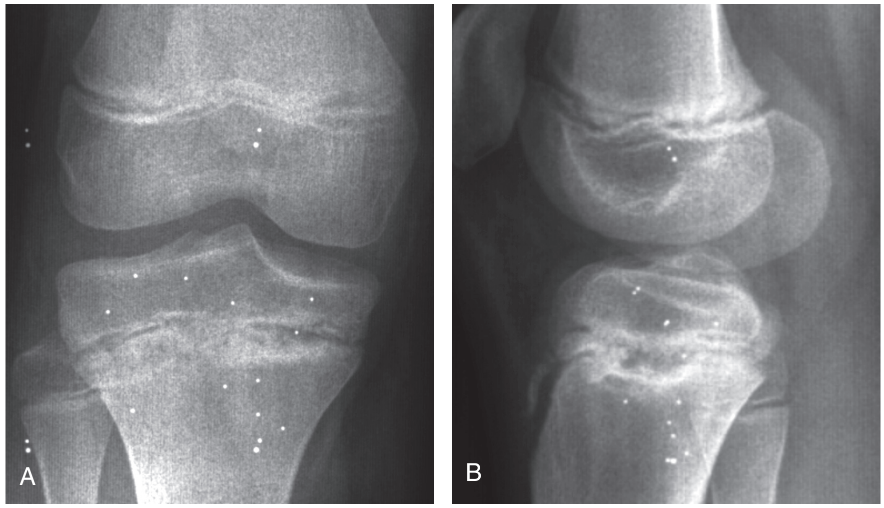

Figure 3. Low-dose radiographs (same patient, same day). There were tantalum markers in the tibia and the calibration cage. A. AP view. B. Lateral view.

surgery. HS supervised the study and assisted with the surgical procedures. TK and AHP performed the statistical analysis. All of the co-authors revised and approved the manuscript.

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No competing interests declared.

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