Original Clinical Article

JOURNAL OF CHILDREN'S ORTHOPAEDICS

Long-term results and comparison of the Green-Anderson and multiplier growth prediction methods after permanent epiphysiodesis using Canale's technique

K. Burger[1]
S. Farr[1]
J. Hahne[2]
C. Radler[1]
R. Ganger[1]

Abstract

Purpose The aim of the study was to evaluate the accuracy and radiographic outcomes of Canale's method in patients with idiopathic leg-length discrepancy (LLD) following percutaneous epiphysiodesis. The accuracy of two common growth prediction methods was assessed.

Methods A total of 18 patients with 26 affected bones (eight distal femur, two proximal tibia, five combined) were clinically and radiologically analyzed after reaching skeletal maturity. We compared the final effect of epiphysiodesis at maturity with the expected effect of epiphysiodesis before surgery; these measures were calculated using the Green-Anderson and multiplier methods, respectively. We furthermore compared pre- and postoperative frontal and lateral plane radiographs.

Results The average LLD was 21.2 mm before surgery and 7.9 mm after epiphysiodesis. The final effect of both methods was not significantly different compared with the expected effect of epiphysiodesis before surgery. However, the prediction by the Green-Anderson method was closer to the definitive epiphysiodesis effect. The frontal plane radiographic deformity parameters did not change significantly after epiphysiodesis. The postoperative sagittal plane radiographic deformity parameters were in the normal range.

Conclusion The Canale technique is a reliable method to reduce LLD in children. With regards to growth prediction, the Green-Anderson method using bone age seems to be more accurate than the multiplier method using chronological age. However, a relative over-estimation was observed with both methods in several cases, which might result in an insufficient correction.

Level of evidence: IV, Therapeutic study

Cite this article: Burger K, Farr S, Hahne J, Radler C, Ganger R. Long-term results and comparison of the Green-Anderson and multiplier growth prediction methods after permanent epiphysiodesis using Canale's technique. *J Child Orthop* 2019;13:423-430. DOI: 10.1302/1863-2548.13.190024

Keywords: permanent epiphysiodesis; Canale; growth prediction; malalignment; multiplier method

Introduction

Permanent epiphysiodesis is a well-established method to correct leg-length discrepancy (LLD) in growing patients. In previous studies, many different techniques have been described to inhibit growth in the longer limb in order to eventually equalize the total leg length.[1-3] In 1933, Phemister was the first to introduce open epiphysiodesis.[2] In 1990, Canale described a percutaneous, minimally invasive technique to disrupt the physis by drilling and subsequent burring/clearing with curettes. This procedure ablates the growth plate of the longer limb irreversibly so that the leg length may become equal at the end of growth.[1]

Intraoperative radiographs are a mandatory requirement to carry out the procedure correctly and to avoid intra-articular joint damage or asymmetric growth arrest. Only a few authors have reported on postoperative development of axis deviation after epiphysiodesis.[4,5] Most importantly, the timing for surgery should be planned accurately to avoid over- or under-correction and to achieve the desired equalization. Using the charts published in 1963 by Anderson et al,[6] it is possible to calculate the remaining growth of the limbs. Furthermore, Paley et al[7] developed age- and gender-related tables based on

[1] Orthopaedic Hospital Speising, Department of Pediatric Orthopaedics and Adult Foot and Ankle Surgery, Vienna, Austria.
[2] Orthopaedic Hospital Speising, Center of Excellence for Orthopedic Pain Management (CEOPS), Vienna, Austria

Correspondence should be sent to Sebastian Farr, Associate Professor of Orthopedic Surgery, Orthopaedic Hospital Speising, Department of Pediatric Orthopaedics and Adult Foot and Ankle Surgery, Speisingertrasse 109, A-1130, Vienna, Austria.
Email: Sebastian.farr@oss.at

limb length databases. With this method, it is possible to estimate the final bone length at skeletal maturity by multiplying the age- and sex-related factors with the immature bone length.

The aims of the study were: 1) to analyze our long-term results following permanent epiphysiodesis in patients with idiopathic LLD using Canale's technique with specific interest in clinical and radiographic outcomes; and 2) to compare the accuracy of two common growth prediction methods in our patient cohort.

Patients and methods

Patient selection

This study was approved by our institutional review board (EK 16-106-0616) and written patient consent was obtained. We queried our institutional database and reviewed 50 patients who underwent a permanent epiphysiodesis (Canale's technique) to correct idiopathic LLD between January 1996 and December 2014. Patients with non-idiopathic LLD, cerebral palsy, skeletal dysplasia, syndrome-associated conditions, trauma history and children with previous knee, ankle or hip surgery were excluded. We only included patients who had a closed physis at the final examination, complete medical reports (e.g. height, age and sex) and standardized preoperative radiographs (anteroposterior (AP) full-length standing radiograph of the lower extremity and/or an orthoroentgenogram and hand radiograph for bone age (BA)). Three patients were excluded: one because of open growth plates and two because of missing radiographs, leading to a total of 47 patients who were invited for a follow-up examination.

We calculated the preoperative BA by comparing hand radiographs with the Greulich and Pyle atlas comprising skeletal developmental pictures of the hand and wrist.[8] For follow-up purposes, an AP full-length standing radiograph of the lower extremity and a full-length standing lateral view radiograph were acquired from each patient.

Growth prediction methodologies: the preoperative remaining growth prediction according to Green and Anderson

To calculate the remaining growth in the distal femur and proximal part of the tibia, we used the Green-Anderson growth-remaining charts.[6] That is, we used the BA and the SD of the patient's height compared with the height of the general population of the same age. The expected length of the femur and tibia at maturity according to Green and Anderson were calculated by adding the predicted remaining growth to the immediate preoperative length of the femur and tibia. We calculated the 'expected LLD at maturity after epiphysiodesis' by subtracting the length of femur and tibia at maturity for the non-operated bones from the immediate preoperative length of the bones that underwent epiphysiodesis. To account for any overcorrected values (that is, one side which was preoperatively longer becomes eventually shorter after epiphysiodesis), we additionally calculated the relative effect of surgery named 'expected effect of epiphysiodesis at maturity'. Therefore, we subtracted the 'expected LLD at maturity after epiphysiodesis' from the preoperative LLD.

Growth prediction methodologies: the preoperative remaining growth prediction according to multiplier method with chronological age (CA)

We calculated the expected LLD at maturity after epiphysiodesis with multiplier tables from Paley et al.[7] In 2000, Paley et al[7] presented the multiplier method using CA to calculate prediction of limb-length discrepancy at maturity. They used the femoral and tibial length data of Anderson et al[9] and developed multiplier tables for the lower limb for male and female patients from birth to 17 years (+ 0 months). To calculate the expected length of the femur and tibia at maturity according the multiplier method we multiplied the age-dependent factors to the preoperative measured bone length of femur and tibia. To calculate 'the expected LLD at maturity after epiphysiodesis' we subtracted the expected leg length at maturity calculated by multiplier tables for the un-operated bones from the preoperative bone lengths that underwent epiphysiodesis. To again account for any overcorrected values after surgery, we calculated the 'expected effect of epiphysiodesis at maturity'. Therefore, we subtracted the 'expected LLD at maturity after epiphysiodesis' from the preoperative LLD.

Radiographic analysis

Radiographs were obtained preoperatively, at follow-up examinations during the postoperative course and at the most recent examination after skeletal maturity. LLD, the mechanical axis and alignment and knee angles were measured on AP full-length standing radiographs. Since it is important to obtain true AP full-length radiographs, patients had to stand with both knees in a strict forward position and the x-ray beam was centred over the patella. Wooden blocks under the shorter limb were used to obtain a levelled pelvis. A 2.5-cm magnification marker was used to calibrate the x-rays.

To calculate the LLD, we measured the femoral (from the top of the femoral head to the bottom of the medial femoral condyle) and tibial (from the middle of a line between the medial and lateral tibial condyle to the tibial plafond) lengths of both legs (Fig. 1).[10] The mechanical axis normally passes through the midpoint of the knee joint (eminentia intercondylaris) or slightly medial (8 mm, SD 7) to it.[11] The origin of the malalignment can be further

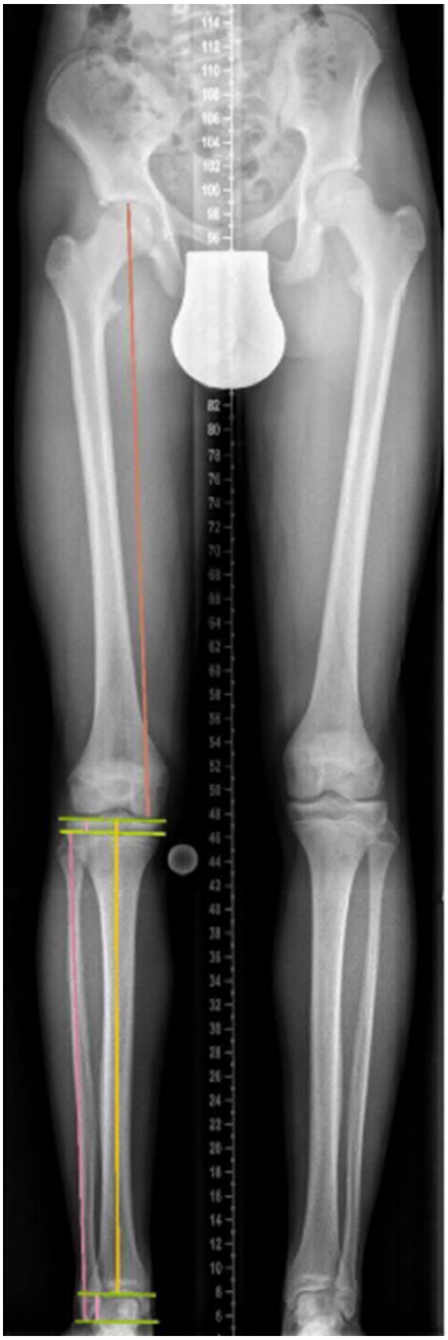

Fig. 1 The preoperative full-length standing radiograph shows a measurement of the femur (red) and the tibia (yellow) on the right leg. We demonstrate the fibula length (purple), the proximal tibio-fibular distance (between green bars, proximal) and the distal tibio-fibular distance (between green bars, distal).

specified by pre-defined frontal plane reference values according to Paley.[11] In two patients we only had preoperative orthoroentgenogramm, so we could not measure frontal plane parameters. For routine preoperative planning, a lateral full-length radiograph before epiphysiodesis is usually not acquired. Thus, we could not compare lateral pre- and postoperative radiographic angles and only assessed postoperative lateral images. However, to calculate the postoperative alignment in the sagittal plane, we used a full-length standing lateral view radiograph of the lower limb with the knee joint maximally extended. The x-ray beam is centred over the knee. The normal range of the mechanical posterior distal femoral angle (mPDFA) is 79° to 87°, whereas it is 77° to 84° for the mechanical posterior proximal tibial angle (mPPTA). Decreased mPDFA and mPPTA indicate a femoral or tibial procurvatum, whereas an increased mPDFA and mPPTA indicate a femoral or tibial recurvatum.[11]

To assess the height of the patella, the Insall-Salvati ratio was measured on a lateral knee radiograph. For this calculation, we divided the patellar tendon length which is the length of the posterior surface of the tendon, from the lower pole of the patella to its insertion on the tibia to the patellar length; this is the greatest pole-to-pole length. Normal values are between 0.8 and 1.2. A decreased ratio indicates a patella baja, whereas an increased ratio indicates a patella alta.[12]

To evaluate the effect of the epiphysiodesis of the tibia on the fibula, we first measured the fibula length (FL) from the top of the fibula head to the bottom of the lateral malleolus. Then we calculated the tibia-fibula ratio (TFR) by dividing the tibial length by the fibular length (TL/FL). Furthermore, we calculated the proximal tibio-fibular (PTF) distance and the distal tibio-fibular (DTF) distance. PTF distance is the distance from the top of the fibular head to the top of the lateral tibial condyle. DTF distance is the distance from the bottom of the lateral malleolus to the tibia plafond. All measurements were obtained by a single paediatric orthopaedic surgeon using the picture archiving communication system (Philips, Hamburg, Germany).

Statistical analysis

Descriptive statistics, including means, minimum and maximum values, SD and medians were calculated. The data were analyzed using the software SPSS version 23 (IM SPSS Statistics, IBM Corp., Armonk, New York). A p-value of 0.05 indicated statistical significance. To compare the expected effect of epiphysiodesis according to Green-Anderson and the multiplier method to the effect of epiphysiodesis after maturity we used the one sample *t*-test. To analyze the radiological outcomes between pre- and postoperative angles and PTF, DTF, TFR and fibula, and differences between PTF, DTF, TFR and FL on the operated and not-operated sides, we used paired *t*-tests.

Results

Demographics

A total of 18 patients (eight female and ten male) with 26 affected bones agreed to participate and were included in the analysis; 29 patients could not be included because of a wrong address, missing preoperative radiographs or they declined to participate (Table 1). The epiphysiodesis locations were the distal femur in eight patients, the proximal tibia in two patients and both the proximal tibia and distal femur in eight patients. In one patient, we also performed a proximal fibular epiphysiodesis. This patient was excluded from analysis. The mean CA at time of surgery was 14.8 years (13.6 to 16.0) for male patients and 13.2 years (11.4 to 14.0) for female patients. In contrast, the mean BA was 13.9 years (12.6 to 15.6) for male patients and 12.9 years (12.0 to 14.6) for female patients. Hence, the overall CA was about half a year higher (mean 14.1 SD 1.2) compared with the overall BA (mean 13.5 SD 1.1). In 16 of 18 patients such a discrepancy of BA to CA existed: in 11 patients BA was lower than CA (mean 1.3 years; SD 0,6); in five patients, BA was higher than the CA (mean 0.7 years; SD 0,3). The mean body height at time of surgery, as measured by growth chart percentiles, was the 62nd percentile (SD 31) for male and female patients. The height of eight patients was above the 75th percentile and below the 25th percentile in four patients.

The mean LLD at surgery measured 21 mm (SD 5.6; 14 to 32) and 8 mm (SD 3.6; 1 to 13) after epiphyseal closing (Table 2). The final LLD after epiphysiodesis was within 15 mm for all cases. In 14 patients (78% of all cases), a discrepancy of < 10 mm was achieved. In two patients, we saw an overcorrection of the shorter leg compared with the preoperative longer leg (+ 3 mm and + 6 mm, respectively).

Table 1 Demographic data

Demographic	
Sex, n	
Male	10
Female	8
Mean chronological age, yrs (range)	
Male	14.8 (13.6 to 16.0)
Female	13.2 (11.4 to 14.0)
Mean bone age, yrs	
Male	13.9
Female	12.9
Epiphysiodesis location, n	
Distal femur	8
Proximal tibia	2
Pan genu	8

Table 2 Radiographic leg-length discrepancy (LLD) measurements before surgery and at maturity

	Preoperative	At maturity
Mean LLD, mm (range)	21 (14 to 32)	8 (1 to 13)
Mean predicted LLD, mm (range)		
Green-Anderson	10 (0 to 38)	NA
Multiplier	16 (2 to 40)	NA

NA, not applicable

Effect of epiphysiodesis according to the Green-Anderson and the multiplier methods

Table 3 outlines the statistical comparison of the two methods in regard to the final effect of epiphysiodesis at maturity. The expected effects of both methods were not significantly different regarding the final effect of epiphysiodesis at maturity after surgery ($p = 0.096$ and $p = 0.051$, respectively). However, the expected effect of epiphysiodesis at maturity according to Green and Anderson's method was closer to the definitive final effect than the multiplier method. Table 4 highlights the comparison of the final effect and the expected effect of epiphysiodesis according both methods with specific interest in sex, growth percentiles and BA. Both prediction methods resulted in overestimation in many male patients and patients with growth over the 75th percentile. In cases where BA was lower than CA, the Green-Anderson method again led to overestimation of the remaining growth. Due to the even smaller number of patients in the subgroups we did not perform a further in-depth statistical analysis.

Frontal and lateral plane parameter

For calculation of the differences between pre- and postoperative parameters we used the angles that were potentially affected by surgery and compared them with the same side on the preoperative radiograph (e.g. lateral distal femoral angle (LDFA) changes of the right side in patients who were operated on the right femur) (Table 5). The frontal plane radiographic deformity parameters (including mechanical axis deviation, mechanical lateral distal femoral angle, mechanical medial proximal tibia angle) did not change significantly after epiphysiodesis. The PTF distance and the TFR, however, decreased and the DTF increased significantly after the treatment. For the Insall-Salvati index, no statistically significant changes were found. Furthermore, we compared the PTF, DTF, FLs and TF ratio between the operated and non-operated limb at final follow-up. There was no significant difference observed with regard to these comparisons. No knee pain was reported on clinical examination. The mean postoperative mPDFA was 81° (SD 2°). The mean postoperative mPPTA was 80° (SD 3°).

Table 3 Statistical analysis of the expected effect of epiphysiodesis with surgery in regards to the final effect of epiphysiodesis with surgery at maturity

	Mean difference, mm	p-value*	*t*-value
According to GA	6.0	0.096	1.764
According to MP	8.8	0.051	2.098

*One-sample *t*-test between final effect of epiphysiodesis at maturity with surgery and the expected effect of epiphysiodesis at maturity with surgery according GA and MP
GA, Green-Anderson method; MP, multiplier method

Table 4 Descriptive analysis of the final and expected effects of epiphysiodesis at maturity

	n	Final effect of epiphysiodesis, mm (SD)	According GA, mm (SD)	According MP, mm (SD)
Male	10	16.3 (8.9)	25.1 (16.7)	32.0 (16.7)
Female	8	13.5 (8.0)	15.9 (8.8)	14.5 (15.5)
> 75th percentile	8	11.4 (7.0)	27.0 (17.7)	30.0 (20.6)
< 75th percentile	10	18.0 (8.5)	16.6 (9.4)	19.1 (14.9)
BA < CA	11	18.0 (5.0)	26.0 (15.9)	NA
BA ≥ CA	7	10.0 (7.8)	13.0 (12.6)	NA

GA, Green-Anderson method; MP, multiplier method; BA, bone age; CA, chronological age; NA, not applicable

Table 5 Radiographic pre- and postoperative deformity parameters

	Preoperative	Postoperative	p-value*†
MAD, mm (SD)	5.2 (4.9)	7.4 (6.2)	0.096
mLDFA, ° (SD)	87.3 (2.0)	87.4 (1.8)	0.880
mMPTA, ° (SD)	87.0 (2.0)	87.4 (1.5)	0.211
PTF, mm (SD)	19.2 (3.8)	13.1 (3.0)	**0.009**
DTF, mm (SD)	22.6 (3.0)	24.0 (2.3)	**0.009**
Fibula length, mm (SD)	382.9 (43.9)	394.0 (37.0)	**0.002**
TF ratio (SD)	0.99 (0.02)	0.96 (0.01)	**0.001**
Insall-Salvati (SD)	1.14 (0.1)	1.07 (0.1)	0.099
	Operated limb	**Non-operated limb**	**p-value***
PTF, mm (SD)	13.1 (3.0)	14 .1(1.8)	0.215
DTF, mm (SD)	24.0 (2.3)	22.6 (2.4)	0.302
Fibula length, mm (SD)	394.0 (37.0)	386.6 (65.3)	0.665
TF ratio (SD)	0.96 (0.01)	0.97 (0.01)	0.088

*Independent *t*-test between pre- and postoperative data and operated and non-operated limb data
†Significant differences are in bold characters
MAD, mechanical axis deviation; mLDFA, mechanical lateral distal femoral angle; mMPTA, mechanical medial proximal tibia angle; PTF, proximal tibio-fibular; DTF, distal tibio-fibular; TF, tibia-fibula

Discussion

In this study we assessed long-term results of Canale's method and judged the accuracy of common LLD predictions by comparing the final effect of epiphysiodesis (at maturity) with the expected effect of epiphysiodesis according to the multiplier and Green-Anderson methods. We were able to include a very homogeneous cohort of 18 patients with exclusively idiopathic LLD. Many of our patients were rather close to skeletal maturity – a growth period wherein a precise growth prediction is usually difficult and often inaccurate.

The effect of epiphysiodesis, when meticulously timed, is described as an appropriate procedure to address moderate LLD in an immature patient. Our results show that all patients had an LLD of less than 15 mm and 78% had an LLD even less than 10 mm at maturity. In our selected patient population, there was no significant difference between both methods regarding the final effect of epiphysiodesis at maturity. The calculation of the expected effect of epiphysiodesis using the multiplier method was different (that is, more inaccurate) compared with the final effect of epiphysiodesis when using the growth prediction method by Green and Anderson. Thus, we tend to recommend the Green-Anderson method over the multiplier method or to include BA for an epiphysiodesis calculation.

One important factor observed during our analysis was that both prediction methods resulted in an overestimation in many male patients and patients with growth over the 75th percentile. Moreover, in cases where BA was lower than CA, the Green-Anderson method again led to overestimation of the remaining growth, potentially resulting in an insufficient correction. In cases with BA and CA being equal or BA being higher than CA, the Green-Anderson method was more accurate. This finding aligns with the results from Lee et al,[13] who also found an overcorrected value.

In 2000, Paley et al[7] presented the multiplier method using CA as a simple and rapid method to calculate prediction of limb-length discrepancy at maturity. The prediction of final LLD was demonstrated to be even more accurate in the female person after modifying the CA according to the menarche.[14] However, the accuracy of the multiplier method is inconsistent, on the basis of previous studies.[10,13,15,16] Aguilar et al[15,16] compared the Moseley straight-line graph to the multiplier method. They found that the multiplier method predicts LLD and the outcome of epiphysiodesis better than the Moseley method. Furthermore, there were no significant differences between the calculations using chronological and skeletal age. Lee et al[13] retrospectively reviewed 44 patients after epiphysiodesis and compared the final LLD at maturity with surgery with the expected LLD at maturity with surgery according to Green and Anderson, multiplier and Moseley straight line. They found out that the multiplier method was the least accurate method, whereas the original Green-Anderson method was deemed the most accurate one. Makarov et al[10] also reported that the multiplier method was the least accurate in predicting the lengths of the long and short legs. Their study included 77 patients treated by epiphysiodesis and compared the accuracy of White-Menelaus, the growth-remaining method of Anderson et al,[6] the Moseley straight-line graph (Rotterdam Modification) and the multiplier method (Paley) in predicting leg lengths and residual leg-length discrepancy. Both Lee et al[13] and Makarov et al[10] reported an improved prediction using skeletal age rather than CA. The Moseley straight-line graph[17,18] and the White-Menelaus[19-21] are other methods to predict the outcome of epiphysiodesis. Those two methods and the Green and Anderson method were compared by Little et al.[22] They recommended the use of the Menelaus method as it was as accurate as the others. Since we routinely use the growth-remaining method of Green-Anderson and increasingly the multiplier method in our clinic, we decided to include those two methods in our study.

We found a mismatch of BA and CA of less than 12 months in ten patients (55%) and more than 12 months in six patients (33%). Makarov et al[10] reported a difference of more than one year between skeletal age and CA in 26% of patients. Lee et al[13] noted a mismatch of more than one year between BA and CA in 15.9% and between six months and 12 months in 34.1%. Cundy et al[23] already demonstrated in 1988 that the estimated BA by experienced radiologists was different from CA by more than one year in about 50% of patients. These results might encourage the importance of using BA in calculating the expected LLD.

Reviews about angular deformities after epiphysiodesis are rare.[4,5,24-27] Makarov et al[4] reported that in 28 (3.3%) of 683 patients who had undergone epiphysiodesis using open curettes, the Phemister procedure or percutaneous procedures resulted in angular deformity of the knee, particularly valgus deformity. They mentioned that many of these patients were younger, had a larger LLD and were more likely to have a congenital cause for LD. Other reviews report no or only a few cases of angular deformity.[24,26,27] Surdam et al[24] reported one patient, of a total of 96 patients, with postoperative genu varum. In our study, we did not see any relevant changes in the frontal plane angles. Unlike the report from Makarov et al,[4] we only included patients with idiopathic LLD and excluded patients with any congenital aetiology. Our patients were older (minimum of 11.25 years of age) with a smaller LLD (minimum 14 mm), when compared with the cohort of Makarov et al.[4]

To our knowledge, only Gabriel et al[26] have reported from one sagittal plane deformity. In one of the 29 patients in their study, they observed a genu recurvatum of the femur after epiphysiodesis. The mean values for postoperative mPDFA and mPPTA were still in the normal range in our cohort; however, we could not delineate any changes due to the lack of preoperative lateral images.

A risk after epiphysiodesis on the fibula is injury of the peroneal nerve.[4] One strategy to avoid this is not to perform the procedure. This results in fibula overgrowth in most cases.[28-30] McCarthy et al[28] reported that fibular overgrowth was significantly higher in patients who were treated with proximal epiphysiodesis of the tibia (PTE) compared with the patients who additionally were operated with an epipyhsiodesis of the proximal fibula (PFE). Only one of 33 patients who underwent a PTE complained about symptoms related to fibular overgrowth. On the basis of experience, since the fibula becomes prominent at an overgrowth of 1 cm and symptoms occur at a much larger overgrowth, they suggest an epiphysiodesis of the fibula when a fibula overgrowth of more than 1 cm to 2 cm is expected. In our study population, only one patient had an additional epiphysiodesis of the fibula. This patient was excluded, and we only included patients who had an epiphysiodesis on the tibia to evaluate changes in PTF, DTF, FL and TF-ratio. Our study demonstrates that a PTE performed without concomitant PFE leads to reduced PTF distance and TF ratio and to an increased DTF distance and FL. Our patients did not report any symptoms around the knee. In order to avoid peroneal nerve injury, we therefore recommend not performing an epiphysiodesis of the proximal fibula in patients with mild LLDs. It might, however, be necessary in cases of larger LLDs and if a fibula overgrowth of more than 1 cm to 2 cm is expected.[28] Finally, there are no reports about changes in patella positions after such procedures, and we also did not find any significant changes in the Insall-Salvati ratio in the limited amounts of images that were available for analysis.

The present study has several limitations. Firstly, we included a rather small number of cases. Therefore, our investigation of, e.g. overestimation on the effect of epiphysiodesis using both methods, was limited. Due to the fact that our patients were relatively 'mature' based on their age, the remaining growth was hence relatively minor. As a consequence, both prognostic methods would have likely shown more pronounced differences in case of more remaining growth. Further, the mean preoperative LLD was low and for some cases borderline for surgery. However, patients and parents frequently opt for this technique even in small LLDs of, e.g. 16 mm to 20 mm, to avoid shoe lifts. Moreover, larger LLDs are increasingly treated with limb lengthening, especially now that intramedullary lengthening is more commonly performed. We did not acquire lateral preoperative radiographs using full-length standing radiographs. Consequently, we were not able to compare pre- and postoperative lateral plane parameters to detect the effect of epiphysiodesis on lateral growth. Further studies are necessary to determine a correlation between lower mPPTA and mPDFA and percutaneous epiphysiodesis. Before the AP full-length standing radiographs, only orthoroentgenograms could be used to assess limb-length discrepancy on imaging studies. Therefore, in some patients, we could not measure the preoperative frontal plane parameter. We excluded those patients when pre- and postoperative plane parameters were compared. Lastly, by using Canale's technique, it is not possible to visualize the local effects of epiphysiodesis as well as with other methods.[31,32]

In conclusion, epiphysiodesis is an effective surgery to decrease LLD. When compared, the two methods to calculate the effect of epiphysiodesis were not significantly different regarding final effect after epiphysiodesis. However, the Green-Anderson growth prediction method using BA seems to be more accurate than the multiplier method using CA. A relative overestimation of both methods was observed in several cases, which might result in insufficient correction. Furthermore, we did not see any postoperative axis deviations, besides a significant reduction of the TF ratio and changes in the PTF and DTF distances; these results need to be further evaluated.

Received 21 February 2019; accepted after revision 31 May 2019.

COMPLIANCE WITH ETHICAL STANDARDS

FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

OA LICENCE TEXT

ETHICAL STATEMENT

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

ICMJE CONFLICT OF INTEREST STATEMENT

RG has received honoraria from Smith&Nephew Inc. (Memphis, TN) and NuVasive Inc. (San Diego, CA). CR has received honoraria from Smith&Nephew Inc. (Memphis, TN) and NuVasive Inc. (San Diego, CA). All other authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

KB: Performed data collection, Data analysis, Wrote the manuscript.

SF: Designed the study, Revised the manuscript.

JH: Performed data analysis.

CR: Revised the manuscript.

RG: Reviewed the manuscript.

REFERENCES

1. **Canale ST, Christian CA.** Techniques for epiphysiodesis about the knee. *Clin Orthop Relat Res* 1990;255:81-85.

2. **Phemister DB.** Operative arrestment of longitudinal growth of bones in the treatment of deformities. *J Bone Joint Surg [Am]* 1933;15-A:1-15.

3. **Métaizeau JP, Wong-Chung J, Bertrand H, Pasquier P.** Percutaneous epiphysiodesis using transphyseal screws (PETS). *J Pediatr Orthop* 1998;18:363-369.

4. **Makarov MR, Dunn SH, Singer DE, et al.** Complications associated with epiphysiodesis for management of leg length discrepancy. *J Pediatr Orthop* 2018;38:370-374.

5. **Gorman TM, Vanderwerff R, Pond M, MacWilliams B, Santora SD.** Mechanical axis following staple epiphysiodesis for limb-length inequality. *J Bone Joint Surg [Am]* 2009;91-A:2430-2439.

6. **Anderson M, Green WT, Messner MB.** Growth and predictions of growth in the lower extremities. *J Bone Joint Surg [Am]* 1963;45-A:1-14.

7. **Paley D, Bhave A, Herzenberg JE, Bowen JR.** Multiplier method for predicting limb-length discrepancy. *J Bone Joint Surg [Am]* 2000;82-A:1432-1446.

8. **Greulich WW, Pyle SI.** *Radiographic atlas of skeletal development of the hand and wrist* (2nd edition). Stanford: Stanford University Press, 1999.

9. **Anderson M, Messner MB, Green WT.** Distribution of lengths of the normal femur and tibia in children from one to eighteen years of age. *J Bone Joint Surg [Am]* 1964;46-A:1197-1202.

10. **Makarov MR, Jackson TJ, Smith CM, Jo CH, Birch JG.** Timing of epiphysiodesis to correct leg-length discrepancy: a comparison of prediction methods. *J Bone Joint Surg [Am]* 2018;100:1217-1222.

11. **Paley D.** *Principles of deformity correction* (2nd edition). Berlin, Heidelberg: Springer, 2003.

12. **Insall J, Salvati E.** Patella position in the normal knee joint. *Radiology* 1971;101:101-104.

13. **Lee SC, Shim JS, Seo SW, Lim KS, Ko KR.** The accuracy of current methods in determining the timing of epiphysiodesis. *Bone Joint J* 2013;95-B:993-1000.

14. **Aird JJ, Cheesman CL, Schade AT, Monsell FP.** Validation of the multiplier method for leg-length predictions on a large European cohort and an assessment of the effect of physiological age on predictions. *J Child Orthop* 2017;11:71-76.

15. **Aguilar JA, Paley D, Paley J, et al.** Clinical validation of the multiplier method for predicting limb length at maturity, part I. *J Pediatr Orthop* 2005;25:186-191.

16. **Aguilar JA, Paley D, Paley J, et al.** Clinical validation of the multiplier method for predicting limb length discrepancy and outcome of epiphysiodesis, part II. *J Pediatr Orthop* 2005;25:192-196.

17. **Moseley CF.** A straight-line graph for leg-length discrepancies. *J Bone Joint Surg [Am]* 1977;59-A:174-179.

18. **Moseley CF.** A straight line graph for leg length discrepancies. *Clin Orthop Relat Res* 1978;136:33-40.

19. **White JW, Stubbins SG.** Growth arrest for equalizing leg lengths. *JAMA* 1944;126:1146-1149.

20. **Menelaus MB.** Correction of leg length discrepancy by epiphysial arrest. *J Bone Joint Surg [Br]* 1966;48-B:336-339.

21. **Westh RN, Menelaus MB.** A simple calculation for the timing of epiphyseal arrest: a further report. *J Bone Joint Surg [Br]* 1981;63-B:1-14.

22. **Little DG, Nigo L, Aiona MD.** Deficiencies of current methods for the timing of epiphysiodesis. *J Pediatr Orthop* 1996;16:173-179.

23. **Cundy P, Paterson D, Morris L, Foster B.** Skeletal age estimation in leg length discrepancy. *J Pediatr Orthop* 1988;8:513-515.

24. **Surdam JW, Morris CD, DeWeese JD, Drvaric DM.** Leg length inequality and epiphysiodesis: review of 96 cases. *J Pediatr Orthop* 2003;23:381-384.

25. **Timperlake RW, Bowen JR, Guille JT, Choi IH.** Prospective evaluation of fifty-three consecutive percutaneous epiphysiodeses of the distal femur and proximal tibia and fibula. *J Pediatr Orthop* 1991;11:350-357.

26. **Gabriel KR, Crawford AH, Roy DR, True MS, Sauntry S.** Percutaneous epiphyseodesis. *J Pediatr Orthop* 1994;14:358-362.

27. **Horton GA, Olney BW.** Epiphysiodesis of the lower extremity: results of the percutaneous technique. *J Pediatr Orthop* 1996;16:180-182.

28. **McCarthy JJ, Burke T, McCarthy MC.** Need for concomitant proximal fibular epiphysiodesis when performing a proximal tibial epiphysiodesis. *J Pediatr Orthop* 2003;23:52-54.

29. **Goedegebuure WJ, Jonkers F, Boot AM, et al.** Long-term follow-up after bilateral percutaneous epiphysiodesis around the knee to reduce excessive predicted final height. *Arch Dis Child* 2018;103:219-223.

30. **Stephens DC, Herrick W, MacEwen GD.** Epiphysiodesis for limb length inequality: results and indications. *Clin Orthop Relat Res* 1978;136:41-48.

31. **Azzolino AM, Herzenberg JE.** Air physiogram: technique for visualization of the resected physis in percutaneous epiphysiodesis. *Orthopedics* 2015;38:170-174.

32. **Ledesma JB, Wang T, Desmond E, et al.** Endoscopic-assisted epiphysiodesis: technique and 20-year experience. *J Pediatr Orthop B* 2016;25:24-30.