Bone age assessment by dual-energy X-ray absorptiometry in children: an alternative for X-ray?

^{1,2}D H M HEPPE, MSc, ^{1,2,3}H R TAAL, MD, ^{1,2}G D S ERNST, MSc, ³E L T VAN DEN AKKER, MD, PhD, ⁴M M H LEQUIN, MD, PhD, ³A C S HOKKEN-KOELEGA, MD, PhD, ^{1,2,3}J J M GEELHOED, MD, PhD and ^{1,2,3}V W V JADDOE, MD, PhD

¹The Generation R Study Group, and Departments of ²Epidemiology, ³Paediatrics and ⁴Radiology, Erasmus Medical Center, 3000 CA Rotterdam, The Netherlands

Objective: The aim of the study was to validate dual-energy X-ray absorptiometry (DXA) as a method to assess bone age in children.

Methods: Paired dual-energy X-ray absorptiometry (DXA) scans and X-rays of the left hand were performed in 95 children who attended the paediatric endocrinology outpatient clinic of University Hospital Rotterdam, the Netherlands. We compared bone age assessments by DXA scan with those performed by X-ray. Bone age assessment was performed by two blinded observers according to the reference method of Greulich and Pyle. Intra-observer and interobserver reproducibility were investigated using the intraclass correlation coefficient (ICC), and agreement was tested using Bland and Altman plots.

Results: The intra-observer ICCs for both observers were 0.997 and 0.991 for X-ray and 0.993 and 0.987 for DXA assessments. The interobserver ICC was 0.993 and 0.991 for X-ray and DXA assessments, respectively. The mean difference between bone age assessed by X-ray and DXA was 0.11 years. The limits of agreement ranged from –0.82 to 1.05 years, which means that 95% of all differences between the methods were covered by this range.

Conclusions: Results of bone age assessment by DXA scan are similar to those obtained by X-ray. The DXA method seems to be an alternative for assessing bone age in a paediatric hospital-based population.

Received 1 March 2010

Revised 3 May 2010

Accepted 13 May 2010

DOI: 10.1259/bjr/23858213

© 2012 The British Institute of Radiology

Children with the same chronological age often have a different bone maturation as a consequence of various genetic and social factors [1–3]. Bone age is a useful indicator of children's growth and biological maturation and is frequently assessed in paediatric endocrinology to determine delayed or advanced growth [4–7]. In children with growth disorders, regular hand X-rays are needed to follow skeletal development at an interval of once or twice per year [8–10]. The classical method to assess bone age is based on the recognition of changes in the maturity indicators in hand–wrist X-rays by comparison with a reference atlas (Greulich and Pyle method) [11].

The main problem with this method is the exposure to a certain amount of irradiation involved in X-ray procedures [12–14]. Although the precise risk estimate of paediatric cancers due to diagnostic X-ray exposure is not known [15–17], we know that the lifetime attributable risk of cancer due to one single X-ray exposure in childhood approximates 15% per sievert [18]. To avoid detrimental effects in later life as a result of cumulative radiation exposure, dose reduction is therefore particularly important in childhood [18, 19]. Consequently, methods involving less radiation would be preferable to assess bone age

in children. Dual-energy X-ray absorptiometry (DXA) has been suggested as a safer method to assess bone age [20]. In both children and adults, DXA is currently widely used to measure bone mineral density for the assessment of osteoporosis [21]. When applied to assess bone age, a hand–wrist scan by DXA (0.0001 mSv) produces a 10-fold lower effective dose than a hand–wrist X-ray (0.001 mSv) [22].

One previous study in a paediatric population of 60 Polish subjects (5–20 years old) suggested that results for bone age assessment by DXA are similar to those produced by X-ray [20]. However, their results were presented as correlation coefficients and *t*-test analysis. For methods of comparison, Bland and Altman analysis is a more appropriate analysis, since it investigates agreement [23, 24]. Also, they used a reference method that applied to the Polish population [25], whereas the Greulich and Pyle method would be more generalisable [3].

Thus far, the accuracy of the assessment of bone age in children using DXA scans has not been properly validated. Therefore, the aim of this study was to investigate whether hand–wrist bone age assessment by DXA produces similar results to the classical X-ray method.

Materials and methods

Subjects

Participants were selected from the outpatient clinic of the Department of Paediatric Endocrinology of the

Address correspondence to: Dr Vincent Jaddoe, The Generation R Study Group (Room AE006), Erasmus MC, PO Box 2040, 3000 CA, Rotterdam, The Netherlands. E-mail: v.jaddoe@erasmusmc.nl

Funding: This study was supported by the Erasmus Medical Center Rotterdam and the Netherlands Organization for Health Research and Development (ZonMw 21000074). The study sponsors had no role in study design, data analysis, interpretation of data or writing this report.

Erasmus Medical Center, Sophia Children's Hospital, Rotterdam, the Netherlands. From April until September 2009, we invited children who were already planned to have a hand-wrist X-ray for medical reason to participate in this study. If written informed consent was obtained, participants had an additional hand-wrist DXA scan immediately after their planned X-ray examination. The medical ethics committee of the Erasmus Medical Center approved this study.

Data collection

All hand-wrist X-rays were performed by qualified technicians at the Department of Radiology according to their usual "hand-wrist for bone age" guidelines: the patient was seated next to the X-ray table, placing his or her left hand and wrist on a double-layered phosphor cassette. The hand was positioned flat, with no radial or ulnar deviance. The X-ray tube was focused on the metacarpalia. The whole hand and wrist was required to be on the X-ray to assess all epiphyses. The settings of the X-ray machine differed according to age group. For children aged <7 years, a standardised modus of 40 kV and 1.60 mAs was used, with a radiation time of 0.837 s, and for children aged ≥ 7 years, we used 42 kV tube voltage and 1.60 mAs, with a radiation time of 0.778 s. The radiographs were uploaded to the electronic hospital information system for offline scoring afterwards.

Subsequently, each participant underwent a DXA scan (iDXA; General Electric, formerly Lunar Corp., Madison, WI) of the left hand on the same day. All scans were performed by one of the two involved investigators using a standardised modus of 100 kV and 0.188 mAs.

All DXA scans were obtained using the same device and software. Children were scanned in a supine position to enable even the younger children to keep their hand still for 66 s (actual scan duration). The left hand was placed in a flat position on the table. The scan was focused on the hand, using a starting point of two finger widths below the radiocarpal articulation, to obtain an image of all hand bones including the wrist and distal radius. Prior to the analysis, we decided to exclude scans or radiographs with major interpretation difficulties due to movement artefacts. Examples of a radiograph and a DXA are given in Figure 1.

Bone age assessment

To blind the assessments, all radiographs and DXA images were stored in a file from which patient characteristics (*i.e.* the subject's name and calendar age) were deleted. Two well-trained observers (observers 1 and 2) independently assessed all patients' bone ages, twice by X-ray and twice by DXA scan, to enable estimation of both intra- and interobserver variability. To avoid recall bias, we first assessed all radiographs followed by all DXA images before we started repeated measurements. An interval of >1 week was kept between the first and second assessments of one image.

A patient's bone age was assessed by comparing the maturity indicators on the patient's radiograph or DXA scan to the standardised reference atlas according to the Greulich and Pyle method. If the patient's bone age was considered to be in between two adjacent standards, the intermediate value was appointed to the patient [11]. Bone age was assessed with a maximum precision of 0.5 years.

Figure 1. (a) Hand-wrist image derived by X-ray of a 12-year-old girl with hypophyseal insufficiency and growth hormone substitution therapy. (b) Hand-wrist image derived by dual-energy X-ray absorptiometry of the same 12-year-old girl with hypophyseal insufficiency and growth hormone substitution therapy.

Table 1. Patient characteristics

	Male (n=48)	Female (n=47)
Height (cm)	139 (94–202)	144 (97–181)
Weight (kg)	34 (13–80)	42 (13–85)
Chronological age (years)	10.4 (2.6–18.1)	10.3 (4.4–17.3)
Age categories n (%)		
0–4 years	2 (4.2)	0 (0)
4–8 years	14 (29.2)	6 (12.8)
8–12 years	13 (27.1)	23 (48.9)
12–16 years	15 (31.3)	16 (34.0)
>16 years	4 (8.3)	2 (4.3)
Bone age (years)		
Based on hand–wrist radiographs	11.6 (2.5–17.0)	11.4 (3.4–16.3)
Based on DXA hand scans	11.3 (2.5–17.0)	11.1 (3.0–16.0)

Values reflect the median (total range) or absolute number (percentage).

Both the radiographs and the DXA scans were assessed using optimal brightness and contrast, which could be adjusted by the observers. In case a dissociated bone development was found between the carpals and the other regions, we focused more on the bone age assigned to the epiphyses of the radius, ulna, metacarpals and phalanges than that assigned to the carpals [26, 27]. We defined dissociated bone development as more than a 1-year difference between the epiphyses of the radius, ulna, metacarpals and phalanges compared with the carpals. We incorporated these adjustments to the Greulich and Pyle method, which has recently been shown to be a valid method in Dutch Caucasian children [28].

Statistical analysis

To compare the two methods of assessing bone age, we used the statistical methods described by Bland and Altman [23, 24]. Firstly, we calculated the intra-observer and interobserver variability using the intraclass and interclass correlation coefficient (ICC) with a 95% confidence interval (CI). In advance, we decided to consider the assessments valid when ICC >0.90. Also, we used Bland and Altman analysis to investigate the difference within the observers and between the two observers.

Secondly, we plotted all X-ray and DXA assessments against the line of equality, which demonstrates the degree of agreement between the two methods. Then, we used Bland and Altman analyses to visualise the difference between the two methods, and its distribution. We calculated the mean and the standard deviation (SD) of the difference to estimate the limits of agreement. In advance, we decided to accept the mean difference between both methods to deviate a maximum of 5% from the mean of both methods. Furthermore, we decided to accept the limits of agreement to be within a range of ± 1 year. Statistical analysis was performed using the Statistical Package for the Social Sciences version 15.0 for Windows (SPSS, Chicago, IL).

Results

In total, 97 (93%) patients agreed to participate in our study. Two patients were excluded because of major

movement artefacts on their DXA scan images. Thus, we were able to assess 95 patients. Patient characteristics and their medical indications are shown in Table 1 and Table 2, respectively. The mean chronological age was 10.4 years, similar for boys and girls. In total, 94% of all children were between the ages of 4 and 16 years.

Table 3 presents all intra-observer and interobserver ICCs for both observations. Intra-observer ICCs were 0.997 and 0.991 for the X-ray assessments and 0.993 and 0.987 for the DXA assessments for observers 1 and 2, respectively. The interobserver ICC was 0.993 for the X-ray and 0.991 for the DXA assessments. The intra-observer and interobserver variability of the second observation were similar.

The means for all the intra-observer and interobserver differences with the limits of agreement (mean $\pm$ 1.96 SD) are listed in Table 4. Values are based on Bland and Altman analyses. The observed mean differences for intra-observer differences ranged from 0.03 (0.78%) to 0.06 (0.88%) years and for interobserver differences from 0.07 (0.91%) to -0.11 (1.51%) years.

Figure 2 shows a plot of the X-ray and DXA assessments against the line of equality. All paired assessment points, within a wide range, lie close to the line of equality, indicating good agreement and suggesting small differences between the methods. Moreover, all points seem to lie randomly around this line, indicating an apparent lack of systematic bias.

Table 2. Medical indications for bone age assessment

	(n=95)
Abstinence syndrome	1 (1.1)
Adrenogenital syndrome	8 (8.4)
Short/tall stature	37 (39.0)
Galactosaemia	1 (1.1)
Growth hormone insensitivity	3 (3.2)
Hypogonadism	2 (2.1)
Hypochondroplasia	1 (1.1)
Hypopituitarism	17 (17.9)
Leri–Weill syndrome	1 (1.1)
Obesity (morbid)	2 (2.2)
Pubertas praecox/tarda	9 (9.5)
Silver–Russell syndrome	1 (1.1)
Turner syndrome	12 (12.6)

Values reflect the absolute number (percentage).

Table 3. Intra- and interobserver intraclass correlation coefficient and 95% confidence interval for all X-ray and dual-energy X-ray absorptiometry (DXA) assessments

Observer	Method	Intraobserver ICC (95% CI)
1	X-ray	0.997 (0.995, 0.998)
	DXA	0.993 (0.989, 0.995)
2	X-ray	0.991 (0.987, 0.994)
	DXA	0.987 (0.981, 0.991)
Observer	Method	Interobserver ICC (95% CI)
1	X-ray	0.993 (0.989, 0.995)
	DXA	0.991 (0.983, 0.992)
2	X-ray	0.992 (0.987, 0.994)
	DXA	0.991 (0.987, 0.994)

CI, confidence interval; ICC, intraclass correlation coefficient.

Figure 3 shows the Bland and Altman plot in which, for each subject, the difference between the X-ray and DXA assessments is plotted against the mean of these X-ray and DXA assessments. This figure applies to the mean of all X-ray assessments and the mean of all DXA assessments. Separate analyses of both observers are shown in Figures 4 and 5. The limits of agreement ($\text{mean} \pm 1.96 \text{ SD}$) are plotted in the figure. Differences between X-ray and DXA assessments were normally distributed.

Following this Bland and Altman plot, the mean difference between the X-ray and DXA assessments was 0.11 (1.95%) years with corresponding limits of agreement of -0.82 and 1.05 years (Table 4). The mean difference did not significantly differ from zero, indicating lack of systematic differences. Results for each observer are demonstrated in Table 5.

Discussion

We observed high intra- and interobserver correlations for both the DXA and the X-ray method and high agreement between bone age assessments performed by DXA and X-ray. The Bland and Altman plots, as well as the simple plot of one method against the other, visualised very high agreement between both methods. The mean difference between the methods did not deviate more than 5% from the mean of both methods, which we defined prior to the study to be the maximum

acceptable difference. The limits of agreement were around the defined -1 and 1 -year limit. Our results suggest that both methods assess bone age with a very small difference and that 95% of all coupled assessments did not differ by more than 1 year. According to this level of agreement, the DXA method produces similar results to the common X-ray method.

To our knowledge, only one previous study compared bone age assessment performed by X-ray and DXA [20]. This study was conducted in 2004 in 50 Polish children (aged 5–18 years) free from any chronic diseases and 10 (aged 8–20 years) with multihormonal pituitary deficiency. The authors used a different type of DXA scan (Expert-XL Densitometer; General Electric, formerly Lunar Corp.) and another reference method to assess bone age, which was more applicable to the Polish population [25]. DXA hand scans and classical hand-wrist radiographs were evaluated by two independent observers. They described a high correlation and no significant difference between mean bone age based on radiographs and DXA hand scans. Likewise, they concluded that the DXA scan produces similar results to the classical method. However, their conclusion was based on correlation coefficients and *t*-test analyses, whereas in measurement studies a more accurate statistical method to apply is the Bland and Altman analysis [24]. Our study and their study used different statistical analyses, but both suggested good agreement.

Another strength of our study is that our study population covers a wide range of different ages and medical indications. We were able to compare the DXA method over a wide range of ages in children who have indications for an X-ray bone age assessment in clinical practice. By including children who were already planned to have a bone age assessment by X-ray for a medical indication, we avoided a substantial amount of extra exposure to radiation to healthy children. We do not consider the hospital-based population instead of a community-based population to be a major limitation, because in clinical practice only children with these medical indications have bone age assessments. Also, because our results were based on comparisons within each subject, we expect our results to be valid for other populations. However, this needs further study.

Table 4. Variation in intra-observer assessments and interobserver assessments and between methods in absolute terms and in proportions of the mean, with the limits of agreement

Assessment		Mean difference		95% limits of agreement (years)	
		Years	Percentage	Lower limit	Upper limit
Intraobserver					
Observer 1	X-ray	0.04	0.69	-0.72	0.80
	DXA	0.06	0.88	-1.17	1.29
Observer 2	X-ray	0.05	0.70	-1.22	1.33
	DXA	0.03	0.78	-1.59	1.65
Interobserver					
Observation 1	X-ray	-0.11	1.51	-1.29	1.07
	DXA	0.09	1.01	-1.42	1.61
Observation 2	X-ray	-0.09	1.50	-1.35	1.16
	DXA	0.07	0.91	-1.26	1.40
Between methods					
Mean		0.11	1.95	-0.82	1.05

DXA, dual-energy X-ray absorptiometry.

Values are based on Bland and Altman plots [23, 24].

Figure 2. Bone age assessed by X-ray and dual-energy X-ray absorptiometry (DXA) scan, with the line of equality.

A drawback of using the DXA scan in bone age assessments is that it is a more time-consuming procedure. The scan lasts 66 s whereas an X-ray examination takes less than 1 s. This might be relevant for movement artefacts in children. Although there might be time-saving opportunities in patients who also need a total-body DXA scan, overall, the DXA scan remains a more time-consuming method. Because assessment of logistics and cost-effectiveness was not part of our study, this needs to be further investigated. A limitation of this study may be the possibility of recall bias, a general issue in intra-observer studies. By first assessing bone age in all X-ray and DXAs before we started with the repeated assessment (interval >1 week), we avoided recall bias as much as possible. If present, recall bias would have affected only the intra-observer variability. We do not expect that this is the case.

For the bone age assessment, we used the Greulich and Pyle reference method. For that reason, we are unsure whether these study results will also apply to the Tanner and Whitehouse method. Since the introduction of the Tanner and Whitehouse standards, many studies have been accomplished to compare the validity of both reference methods [29–33]. Currently, there is no overall agreement on preference of method. It has been claimed that the Tanner and Whitehouse method produces slightly more precise results, but this was shown only in one of the studies [33]. The Greulich and Pyle method has considerable practical advantages. Probably because this method is less time-consuming and requires less specific training, it is still the most commonly used reference method in clinical practice [33].

Figure 3. Bland and Altman plot of the variation between X-ray and dual-energy X-ray absorptiometry assessments. The mean indicates the mean difference, with the 95% limits of agreement. SD, standard deviation.

Figure 4. Bland and Altman plot of the variation between X-ray and dual-energy X-ray absorptiometry assessments: observer 1. SD, standard deviation.

Automatic assessment of bone age is a highly innovative method. It has recently been compared with manual Greulich and Pyle assessments and has shown to produce similar results [33]. A major advantage of this automatic assessment of bone age is absence of intra- and interobserver variability. Further research is needed to investigate whether this automatic assessment of bone age is also applicable to the DXA scan method.

Conclusion

DXA seems to be an alternative method for assessing bone age in a common paediatric hospital-based population. The major advantage of this method compared with the classical method is lower exposure to radiation. Results of this method are of similar accuracy to those obtained by X-ray. Further studies are needed to investigate the cost-effectiveness.

Figure 5. Bland and Altman plot [23, 24] of the variation between X-ray and dual-energy X-ray absorptiometry assessments: observer 2.

Table 5. Variation between methods in absolute terms and in proportions of the mean, with the limits of agreement for each observer

Assessment	Mean difference		95% limits of agreement (years)	
	Years	Percentage	Lower limit	Upper limit
Between methods				
Observer 1, mean	0.02	0.73	−0.85	0.89
Observer 2, mean	0.21	3.21	−1.16	1.57

Values are based on Bland and Altman plots [23, 24].

Acknowledgments

We gratefully acknowledge the contribution of all children who participated in the study. We also thank General Electric, formerly Lunar Corp.

References

- Gilli G. The assessment of skeletal maturation. *Horm Res* 1996;45:49–52.
- Mora S, Boechat MI, Pietka E, Huang HK, Gilsanz V. Skeletal age determinations in children of European and African descent: applicability of the Greulich and Pyle standards. *Pediatr Res* 2001;50:624–8.
- Groell R, Lindbichler F, Riepl T, Gherra L, Roposch A, Fotter R. The reliability of bone age determination in central European children using the Greulich and Pyle method. *Br J Radiol* 1999;72:461–4.
- Sprout A, Peritz E. Assessment of skeletal age in short and tall children. *Am J Phys Anthropol* 1971;35:433–9.
- Bierich JR. [Significance of bone age estimation to the clinic (author's transl)]. *Die Bedeutung der radiologischen Skeletalterbestimmung für die Klinik*. *Radiologe* 1976;16:381–90.
- Heinrich UE. [Significance of radiologic skeletal age determination in clinical practice]. *Die Bedeutung der radiologischen Skeletalterbestimmung für die Klinik*. *Radiologe* 1986;26:212–15.
- Bramswig JH, Fasse M, Holthoff ML, von Lengerke HJ, von Petrykowski W, Schellong G. Adult height in boys and girls with untreated short stature and constitutional delay of growth and puberty: accuracy of five different methods of height prediction. *J Pediatr* 1990;117:886–91.
- Raiti S, Moore WV, Van Vliet G, Kaplan SL. Growth-stimulating effects of human growth hormone therapy in patients with Turner syndrome. *J Pediatr* 1986;109:944–9.
- Kaufman FR, Sy JP. Regular monitoring of bone age is useful in children treated with growth hormone. *Pediatrics* 1999;104:1039–42.
- Fahmy JL, Kaminsky CK, Kaufman F, Nelson MD Jr, Parisi MT. The radiological approach to precocious puberty. *Br J Radiol* 2000;73:560–7.
- Greulich WW, Pyle ID. *Radiographic atlas of skeletal development of the hand and wrist*, 2nd edn. Stanford, CA: Stanford University Press, 1959.
- Shu XO, Potter JD, Linet MS, Severson RK, Han D, Kersey JH, et al. Diagnostic X-rays and ultrasound exposure and risk of childhood acute lymphoblastic leukemia by immunophenotype. *Cancer Epidemiol Biomarkers Prev* 2002;11:177–85.
- Berrington de Gonzalez A, Darby S. Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries. *Lancet* 2004;363:345–51.
- Hall EJ, Brenner DJ. Cancer risks from diagnostic radiology. *Br J Radiol* 2008;81:362–78.
- Wakeford R. Childhood leukaemia following medical diagnostic exposure to ionizing radiation in utero or after birth. *Radiat Prot Dosimetry* 2008;132:166–74.
- Schulze-Rath R, Hammer GP, Blettner M. Are pre- or postnatal diagnostic X-rays a risk factor for childhood cancer? A systematic review. *Radiat Environ Biophys* 2008;47:301–12.
- Linet MS, Kim KP, Rajaraman P. Children's exposure to diagnostic medical radiation and cancer risk: epidemiologic and dosimetric considerations. *Pediatr Radiol* 2009;39:S4–26.
- Hall EJ. Radiation biology for pediatric radiologists. *Pediatr Radiol* 2009;39:S57–64.
- ICRP. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP* 2007;37:1–332.
- Pludowski P, Lebiedowski M, Lorenc RS. Evaluation of the possibility to assess bone age on the basis of DXA derived hand scans—preliminary results. *Osteoporos Int* 2004;15:317–22.
- Njeh CF, Fuerst T, Hans D, Blake GM, Genant HK. Radiation exposure in bone mineral density assessment. *Appl Radiat Isot* 1999;50:215–36.
- Mettler FA Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology* 2008;248:254–63.
- Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–10.
- Bland JM, Altman DG. Applying the right statistics: analyses of measurement studies. *Ultrasound Obstet Gynecol* 2003;22:85–93.
- Kopczynska-Sikorska J. *Atlas radiologiczny rozwoju kości dłoni i nadgarstka*. Państwowy Wydawnictwo Lekarskich: Warsaw, Poland, 1969.
- Acheson RM, Vicinus JH, Fowler GB. Studies in the reliability of assessing skeletal maturity from X-rays. II. The bone-specific approach. *Hum Biol* 1964;36:211–28.
- Roche AF, Davila GH. The reliability of assessments of the maturity of individual hand-wrist bones. *Hum Biol* 1976;48:585–97.
- van Rijn RR, Lequin MH, Robben SG, Hop WC, van Kuijk C. Is the Greulich and Pyle atlas still valid for Dutch Caucasian children today? *Pediatr Radiol* 2001;31:748–52.
- Acheson RM, Vicinus JH, Fowler GB. Studies in the reliability of assessing skeletal maturity from X-rays. 3. Greulich-Pyle Atlas and Tanner-Whitehouse method contrasted. *Hum Biol* 1966;38:204–18.
- Andersen E. Comparison of Tanner-Whitehouse and Greulich-Pyle methods in a large scale Danish Survey. *Am J Phys Anthropol* 1971;35:373–6.
- Milner GR, Levick RK, Kay R. Assessment of bone age: a comparison of the Greulich and Pyle, and the Tanner and Whitehouse methods. *Clin Radiol* 1986;37:119–21.
- King DG, Steventon DM, O'Sullivan MP, Cook AM, Hornsby VP, Jefferson IG, et al. Reproducibility of bone ages when performed by radiology registrars: an audit of Tanner and Whitehouse II versus Greulich and Pyle methods. *Br J Radiol* 1994;67:848–51.
- Bull RK, Edwards PD, Kemp PM, Fry S, Hughes IA. Bone age assessment: a large scale comparison of the Greulich and Pyle, and Tanner and Whitehouse (TW2) methods. *Arch Dis Child* 1999;81:172–3.