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Improved Reliability in Skeletal Age Assessment Using a Pediatric Hand MR Scanner with a 0.3T Permanent Magnet

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The purpose of this study was to improve the reliability and validity of skeletal age assessment using an open and compact pediatric hand magnetic resonance (MR) imaging scanner. We used such a scanner with 0.3-tesla permanent magnet to image the left hands of 88 healthy children (aged 3.4 to 15.7 years, mean 8.8 years), and 3 raters (2 orthopedic specialists and a radiologist) assessed skeletal age using those images. We measured the strength of agreement in ratings by values of weighted Cohen's κ and the proportion of cases excluded from rating because of motion artifact and inappropriate positioning. We compared the current results with those of a previous study in which 93 healthy children (aged 4.1 to 16.4 years, mean 9.7 years) were examined with an adult hand scanner. The κ values between raters exceeded 0.80, which indicates almost perfect agreement, and most were higher than those of the previous study. The proportion of cases excluded from rating because of motion artifact or inappropriate positioning was also reduced. The results indicate that use of the compact pediatric hand scanner improved the reliability and validity of skeletal age assessments.

Keywords: ***pediatric hand scanner, skeletal age assessment, 0.3T permanent magnet MRI***

Introduction

Skeletal age, a biological measure of a child's growth and developmental diseases, is often assessed by rating the maturity of bones in a radiograph of the left hand and wrist.[1–3] The Tanner and Whitehouse (TW_2) system[2] is a popular method in which a rater assigns a maturity stage for bones in the hand and wrist and scores them according to developmental stage. The sum of the scores is transformed into a skeletal age using standards for a skeletal maturity score.

Recently, magnetic resonance (MR) imaging has emerged as a prominent alternative to standard radiography because of its noninvasive and nonirradiative nature.[4–7] In a previous study,[7] we showed the validity of assessing skeletal age using MR imaging for a wide range of ages. We used an open, compact MR imaging system that offered adequate performance with greater comfort than standard radiography. The system is less claustrophobic and more convenient for children because it does not require their sedation. However, the previous study contained some problems. Severe motion artifacts or inappropriate positioning (some bones were imaged outside the field of view [FOV]) precluded skeletal rating in some cases (10.8%), and though the strength of inter-rater agreement was substantial, it was not close to perfect, especially for the radius and some short bones.

We believe these problems were mainly attributable to the large size of the scanner, which was designed to image an adult hand and was too large for very young children (80-cm width × 80-cm depth × 108.4-cm height including a thermal shield, 700 kg in weight). Use of the large scanner limited assessable age. Young subjects with arms too short to reach the center of the imaging volume could not be examined, and subjects with short

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arms whose hands only marginally reached the FOV were examined in an unnatural position, which could have led to unintentional motion. The resulting blurring or ghosting artifacts might have been responsible for rating discrepancies between raters or, in the worst cases, led to exclusion from the rating.

To remedy this problem, we developed a new pediatric hand scanner with a smaller permanent magnet[8] that enhances the openness and compactness of the system and allows examination in a more comfortable position. Using this system, we showed sufficient image quality of the left hand of a 4.9-year-old volunteer for skeletal age assessment. In the current study, we used this scanner to improve the reliability and validity of skeletal age assessment. Furthermore, we changed the protocol for skeletal age examination, imaging the distal and proximal parts separately because the imaging area of the pediatric scanner was too small to image the whole hand at one time. Although this change doubles measurement time, it may help ensure imaging of all bones and reduce the number of cases excluded because of inappropriate positioning. The aim of this study was to show that these improvements would increase the reliability and validity of skeletal age assessment.

Materials and Methods

Subjects

We recruited 88 healthy children (65 boys, 23 girls) aged 3.4 to 15.7 years (mean, 8.8 years) from the local community and excluded those with a history of genetic, developmental, metabolic, or endocrinal diseases or wrist trauma and those on medication, including hormonal supplements. Written informed consent was obtained from both the child and a parent. Table compares examination conditions between the previous[7] and present volunteer studies. The number of volunteers in each study was almost the same. All MR imaging measurements were performed under the approval of the Ethical Committee of the Graduate School of Pure and Applied Sciences of the University of Tsukuba.

MR examinations

We used an open compact MR imager with permanent magnet that was newly developed as a pediatric hand scanner to assess skeletal age. We described the hardware specifications in a previous study.[8] Briefly, the MR imaging system consists of a C-shaped neodymium iron boron (Nd–Fe–B) permanent magnet, solenoid-type radiofrequency probe, gradient coil set, and MR imaging console. The specifications of the magnet circuit were: field strength, 0.3T; gap width, 12 cm; weight, 450 kg; size, 52 cm (width) × 62 cm (depth) × 52 cm (height) including a thermal shield; and homogeneity, 16 ppm over a 12 × 16 × 5-cm diameter ellipsoidal volume. The magnet circuit was about 33% smaller than that of the magnetic circuit of the adult hand scanner[7,9–11] used in the previous study (Figs. 1a, b). The imaging protocol was almost the same as that used in the previous study.[7] To reduce motion, each subject sat in a chair and watched television. We used a flexible cloth belt to affix the subject's hand to a plastic plate as firmly as possible without its being painful and employed a 3-dimensional (3D) coherent gradient-echo sequence (dwell time, 20 μs; repetition time [TR]/echo time [TE], 40/11 ms; FA, 60°; matrix size, 128 × 512 × 32; FOV, 10 cm × 20 cm × 5 cm; and acquisition time for one scan, 2 min 44 s). Though we previously imaged the whole hand at once, in this study, we imaged the proximal and distal parts separately because the imaging area of the scanner was too small to accommodate the whole hand at once.

MR skeletal rating

Three raters (2 orthopedic specialists [A and B] and a radiologist [C]) blinded to the children's ages independently rated skeletal age according to the Tanner-Whitehouse Japan RUS system (RUS stands for radius, ulna, and the 11 short bones in

Table. Differences in materials and methods between the previous and present volunteer studies

	Previous study	Present study
Number of subjects	93 (50 boys, 43 girls)	88 (65 boys, 23 girls)
Age range of subjects	4.1 to 16.4 years (mean 9.7)	3.4 to 15.7 years (mean 8.8)
Scanner type	Adult hand scanner	Pediatric hand scanner
Scanner size and weight	80 cm × 80 cm × 108.4 cm, 700 kg	52 cm × 62 cm × 52 cm, 450 kg
Sequence	3D gradient echo	3D gradient echo
Number of measurements	one	2 (proximal and distal parts)

rays 1, 3, and 5; assessment of skeletal age for Japanese children, Medical View, Tokyo, Japan). Rater A rated each image twice, with a one-week interval between ratings (A1 and A2). Raters B and C rated each image once. We calculated the average values of Cohen's weighted κ[12] between raters to evaluate the consistency of ratings between multiple raters. The average values of κ and the proportion of cases excluded from rating were compared with those calculated from the previous study.[7] The raters also visually checked whether the MR images exhibited artifacts and whether the signal-to-noise ratios (SNRs) were sufficiently high for rating.

In the statistical analysis, we used a simple linear regression analysis to determine correlation between chronological age and MR imaging skeletal age and Pearson's correlation coefficient (r) to measure correlation between chronological and skeletal ages and inter- and intrarater reliability. We performed Welch's *t*-tests on the averaged proportion of cases excluded from rating in the previous and present studies.

Results

MR images

Figure 1c and d show an examination and examples of MR images for the youngest volunteer (3.4 years, 99.8-cm height). As shown in Fig. 1d, no motion artifact was observed in the image. Figure 2 shows examples of MR images obtained with the adult scanner and the new pediatric scanner; image quality was similar between the two. According to the rater's opinions, most images were acquired without noticeable artifacts and with sufficient SNRs to allow MR skeletal rating.

Skeletal age assessment

Figure 3 shows skeletal age rated from MR images as a function of chronological age. As in the previous study, this figure shows a strong positive linear correlation between skeletal and chronological age (Pearson's $r = 0.899$, Rater A1; 0.898, A2; 0.899, B; and 0.912, C). The correlation in skeletal age between different raters was also high ($r =$ 0.918 [A1 versus A2], 0.906 [A1 versus B], 0.882 [A1 versus C], 0.935 [A2 versus B], 0.929 [A2 versus C], and 0.880 [B versus C]), indicating high intra- and inter-rater reliability.

We further evaluated the consistency of rating between raters by the value of Cohen's weighted κ, which indicates the strength of agreement beyond chance.[12] A higher κ value indicates higher consistency, and κ above 0.80 reflects almost perfect agreement. Figure 4a shows inter-rater agreements of the rated developmental stages for different bones. The κ values obtained with the new scanner exceeded 0.80 for most bones and were higher than those obtained with the previous scanner, indicating improved inter-rater agreement. In particular, in this study, the radius and distal phalanx 3 bones

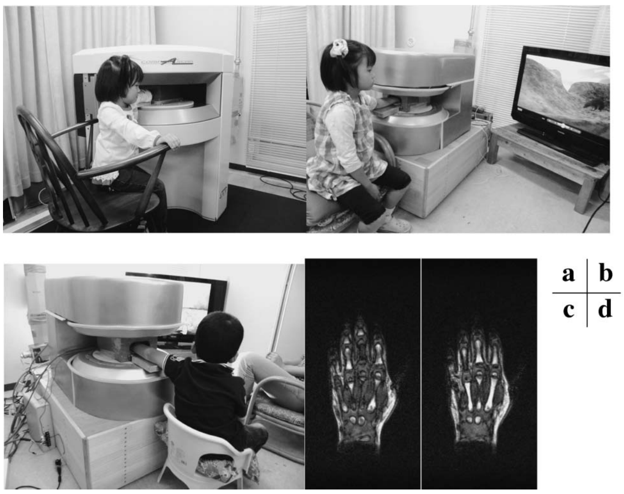

Fig. 1. Comparison of magnetic resonance (MR) scanners used in the (**a**) previous and (**b**) present studies. (**a**) Adult hand scanner, (**b**) pediatric hand scanner, (**c**) snapshot and (**d**) examples of MR images of the youngest volunteer (3.4 years).

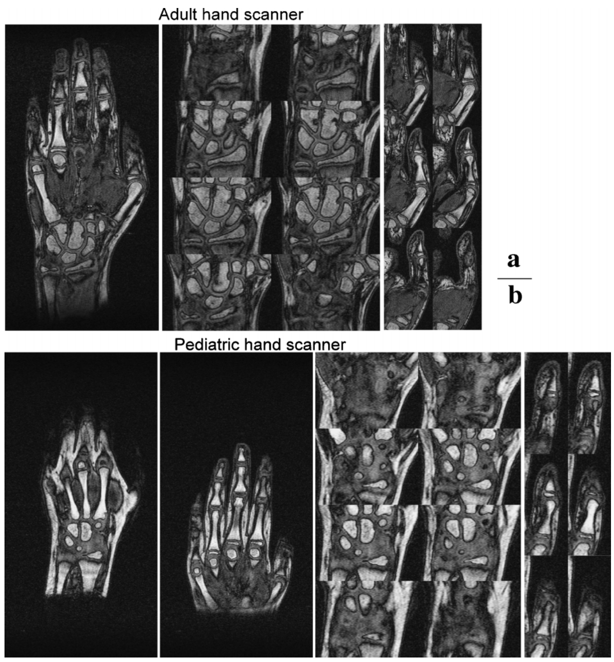

Fig. 2. Comparison of magnetic resonance (MR) images obtained with the (**a**) previous and (**b**) present scanners. The subjects were (**a**) a 10.2-year-old girl and (**b**) a 6.1-year-old girl. Magnified views near the carpal region and thumb are also shown. In (**b**), the cartilages between the carpal bones were seen, although the contrast was not high.

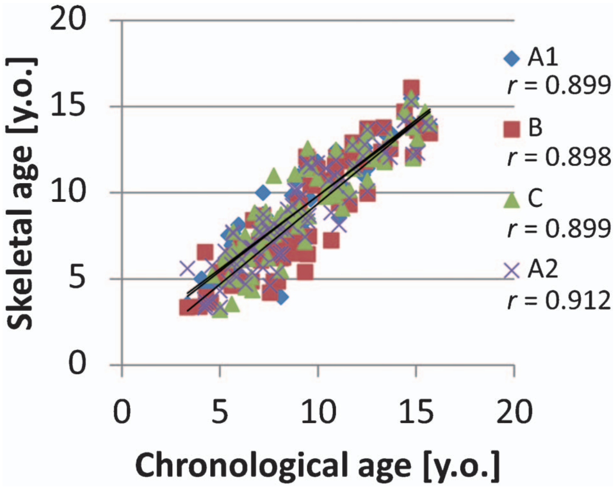

Fig. 3. Correlation between skeletal age rated from magnetic resonance (MR) images and chronological age.

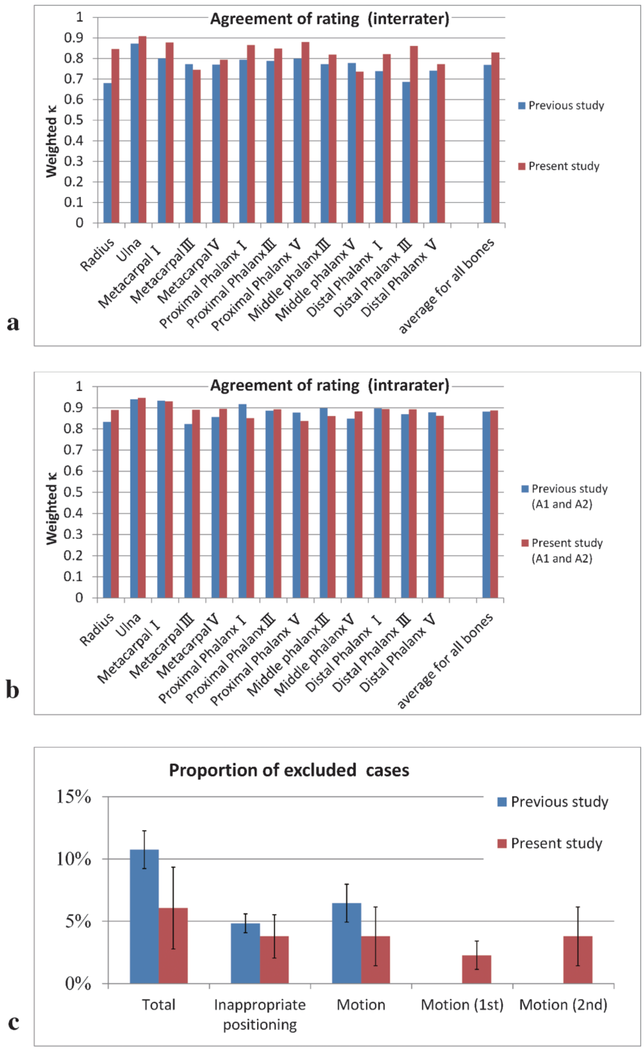

Fig. 4. Evaluation of reliability of skeletal age rating. (**a**), (**b**) Comparison of weighted Cohen's κ between previous and present studies. In (**a**), the κ values were averaged for A1 and B for the previous study and for A1, B, and C for the present study. In (**b**), the κ values were averaged for A1 and A2 for both studies. (**c**) Proportions of cases excluded from rating. The proportions were averaged for A1 and B for the previous study and for A1, B, and C for the present study. The error bars indicate the standard deviations.

were rated as consistently as other bones, whereas they were previously rated less consistently. The ulna, for which there was previously high agreement, was also rated consistently in the present study. Figure 4b shows the intrarater agreement (A1 versus A2). In both studies, the κ values exceeded 0.80 for all bones, indicating almost perfect intrarater agreement.

Figure 4c shows the proportions of cases excluded from rating. The total excluded cases decreased significantly, from 10.3 to 5.3% ($P < 0.05$). The proportion of cases excluded because of inappropriate positioning decreased slightly on average but did not differ significantly from the previous study ($P = 0.33$). The cases excluded because of motion decreased from 6.5 to 3.8%, but the difference was not significant ($P = 0.23$). However, in the present study, motion artifacts appeared less frequently in the first image (distal part) than the second (proximal part), and the cases excluded because of motion for the first image were significantly reduced to 2.0% ($P < 0.01$) compared with the previous study.

Discussion

In most cases, the pediatric scanner provided sufficient image quality to allow MR skeletal rating. This enabled reliable MR rating of skeletal age; the correlation coefficients of skeletal age between raters were significantly high. The κ values showed higher inter- and intrarater consistency than in the previous study (Figs. 4a, b), and the average κ values indicate almost perfect agreement. Furthermore, the total proportion of cases excluded from rating decreased (Fig. 4c). These results indicate the improved reliability and validity of the skeletal age examination in the present study.

To increase the reliability and validity, we made 2 modifications to the examination methods of the previous study; we used a small pediatric hand scanner and imaged the proximal and distal parts separately. Use of the small scanner lowered the age limitation for examination. In the previous study, children younger than 4 years were not included. In the present study, in contrast, the youngest volunteer was 3.4 years old. The use of the small scanner also enhanced the openness and compactness of the system. The distance from the edge of the magnetic circuit to the center, 20 cm, was short enough for the youngest volunteer, for whom no motion artifact was observed in the MR images. It was easy to position the volunteer comfortably during the MR examination in most cases. The use of the small scanner leads to suppression of motion and is therefore responsible for the observed increase in the rating agreement. Indeed, motion artifacts appeared less frequently in the first image (proximal part) ($P < 0.01$) compared with findings in the previous study. However, motion artifact was not significantly suppressed in the second image, probably because the fingers were more mobile than the wrist and the current method for fixing the distal part was not sufficient. The subject could rest for an interval of about 3 min between the 2 scans, so prolongation of the whole examination time would not be responsible for the increase in motion observed in the second images. More stable fixation of the hand or use of a sequence insensitive to motion, such as projection acquisition, may be effective in reducing motion more drastically.

The separate imaging has a potential advantage for improving rating agreement. Several bones were imaged in both the proximal and distal parts, and the image with fewer artifacts could be used for rating. Although we expected that separate imaging would reduce the cases excluded because of inappropriate positioning, this was not clearly observed in Fig. 4c. There were still cases in which the radius, ulna, and distal phalanx bones, which were close to the FOV edge, were not imaged. The hand of each subject was positioned according to line markers drawn on the supporting plate, which indicate the imaging volume. A more appropriate protocol with, for example, a prescan check for positioning is required to address the positioning deficiency.

Conclusion

We examined the skeletal age of children using a compact pediatric scanner and evaluated the reliability and validity of rating. The κ values between raters exceeded 0.80 for all bones, indicating almost perfect agreement, and they were high for most bones compared with findings of our previous volunteer study using an adult scanner. Furthermore, we excluded a smaller proportion of cases from rating than in the previous study, which we attribute mainly to the reduction in the number of cases excluded because of motion artifact. These results demonstrate improved reliability and validity of skeletal age assessment using pediatric hand MR imaging.

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