Four-fold reduction in scan time for skeletal age examination enabled by adaptive compressed sensing MRI

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INTRODUCTION

Skeletal age of a young child can be assessed by rating the maturity stage of left-hand bones in the MRI images. We have used a 0.3 T open scanner to provide a comfortable examination environment for children, and showed the validity of the skeletal age examination [1,2]. However, the long scan times for 3D imaging are uncomfortable for children and often induce motion artifacts in the images. In the previous study [3], we used compressed sensing (CS) to shorten the long scan time, but the acceleration factor (AF) was limited to 2 because of the low signal-to-noise ratio. To further decrease the scan time, it is necessary to optimize the CS sampling pattern for skeletal age examination with knowledge of the nature of data to be reconstructed. Here we optimize the sampling pattern using the database of hand images obtained in the previous study [2] and realize the 40-second scan (AF = 4). Both the simulation and experimental results reveal the validity of the CS-based skeletal examination using optimal sampling.

SIMULATION

Methods: The sampling pattern for CS was optimized using 88 hand images obtained in the previous study [2]. We chose one subset of 12 data (age-specific, 6 boys and 6 girls) which have the high image qualities as a training set and the other subset as a validating set. The original matrix size (full-sampling, FS) was 512 × 128 × 32. Given an AF (2, 3, and 4), the sampling pattern in the k-space was determined as a combination of the low-resolution pattern ($N_x \times N_y$ dense pattern near the center) and undersampled pattern in two phase-encoded directions with the variable density. The probability density function was $A\exp[-(k_x^2+k_y^2)/(2\sigma_x^2+2\sigma_y^2)]$, where k_x and k_y are the coordinates in the phase directions. N_x and N_y were varied between 8 to 32 with 8 increments, σ_x and σ_y were varied between 0.5 and 2 with 0.5 increments, and 5 random patterns were chosen for each parameter set. Then the training set was reconstructed using CS for each of the generated patterns. The sampling pattern with the highest average of the structural similarity (SSIM) over the training set was chosen as the optimal pattern.

Validation: The optimal patterns were validated with the validating set (Fig. 1(a)). We determined the criteria for validation as follows. In the previous study [3], we evaluated the mean absolute error in the skeletal age between FS and CS-based ratings, and found that the error has a negative correlation with the SSIM (Fig. 1(b)). The mean error was 1.0 years and the threshold for SSIM above which the error is less than the mean value was about 0.75. This would give the success criteria for skeletal age assessment using CS. As shown in Fig. 1(a), SSIM>0.75 in most cases and the above criteria is satisfied.

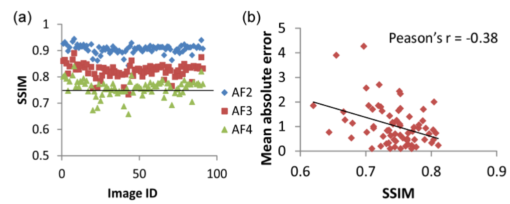


Fig. 1 (a) Validation of the optimal patterns. (b) Mean absolute error in the skeletal age between FS and CS-based ratings in the previous study [3].

EXPERIMENTAL METHODS

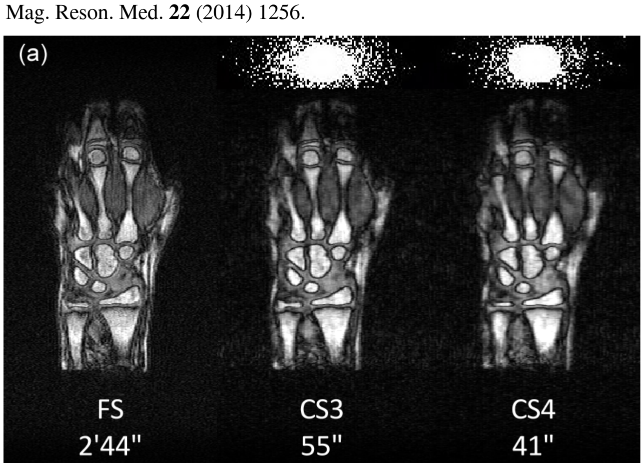
A total of 59 healthy children aged from 4.4 to 15.3 (mean 9.1, 35 boys and 24 girls), were recruited from the local community. Written informed consent was obtained from both the child and one of the parents. All MRI measurements were performed under the approval of the ethical committee of our institute. We used an open and compact MRI scanner optimized for skeletal age examination (field strength = 0.3 T, gap width = 12 cm, size = 57 × 40 × 41 cm^3, weight = 450 kg). A 3D coherent gradient-echo sequence (dwell time = 20 μs; TR/TE = 40/11 ms; FA = 60°; FOV = 20 × 10 × 5 cm^3, total acquisition time = 2 min 44 s for FS) was used twice for each subject to image the distal and proximal parts separately. For CS imaging, the optimal patterns with AF = 3 and AF = 4 were used. Skeletal age was rated independently by two raters (a radiologist A and an orthopedic surgeon B) who were blinded to the children's age, according to the Tanner–Whitehouse Japan RUS system (RUS stands for radius, ulna and the 11 short bones in rays 1, 3 and 5) (Assessment of skeletal age for Japanese children, Medical View, Tokyo, Japan). The rater A rated twice (A1 and A2) to investigate the interrater reproducibility. The values of Cohen's weighted κ [3] were calculated to evaluate agreement of rating for each bone.

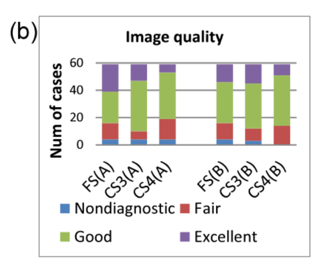
RESULTS AND DISCUSSION

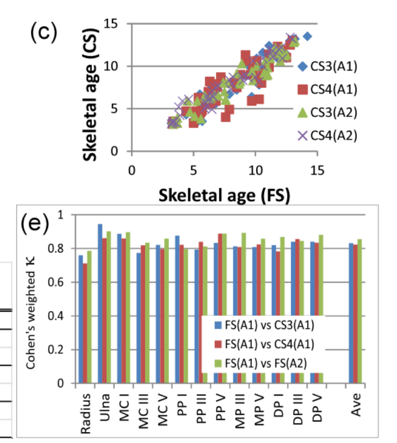
In most cases of the volunteer study, the image quality of CS was compatible with that of FS (Fig. 2(a) and (b)). Figure 2(b) shows that the number of cases where the image quality is good or excellent was large even for CS with AF = 4. The interrater and intrarater reproducibilites for CS-based rating were high (Peason's r = 0.973 (CS3(A1) vs CS3(A2)), 0.874 (CS3(A1) vs CS3(B)), 0.962 (CS4(A1) vs CS4(A2)), and 0.873 (CS4(A1) vs CS4(B))). The skeletal ages rated from the CS images agreed well with those rated from FS images (Fig. 2(c) and (d)). The mean absolute errors in the skeletal age between FS and CS images were within 1.0 years and as small as that between FS(A1) and FS(A2) (Fig. 2(d)). The agreement of CS-based rating for each bone was as high as that of the FS-based rating (Fig. 2(e)). These results indicate the high reliability of CS-based rating.

CONCULSION: Here we demonstrated the validity of the 40-second skeletal age examination using CS-MRI with the optimal sampling patterns.

REFERENCES: [1] Y. Terada et al., Magn. Reson. Med. **69** (2013) 1697. [2] Y. Terada et al., Magn. Reson. Med. Sci. **13** (2014) 215. [3] Y. Terada et al., Proc. Intl. Soc. Mag. Reson. Med. **22** (2014) 1256.







(d)

	Peason's r	mean absolute error [years]
FS(A1) – FS(A2)	0.954	0.70
FS(A1) – CS3(A1)	0.954	0.72
FS(A1) – CS4(A1)	0.899	0.96
FS(A2) – CS3(A2)	0.965	0.68
FS(A2) – CS4(A2)	0.960	0.70
FS(B) – CS3(B)	0.946	0.57
FS(B) – CS4(B)	0.957	0.53

Fig. 2 (a) Optimal sampling patterns and examples of MR images acquired with full sampling (FS), and CS with acceleration factor of 3 (CS3) and 4 (CS4). (8.6 years, girl). (b) Image quality evaluation. (c) Comparison of skeletal ages rated from FS and CS images. (d) Peason's r and mean absolute error between different rating results. (e) Agreement of rating for each RUS bone.