TECHNICAL NOTE

Parallel Imaging of Head with a Dedicated Multi-coil on a 0.4T Open MRI

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Background: Parallel imaging is widely used for cylindrical magnetic resonance imaging (MRI); however, few studies apply parallel imaging to open MRI. We previously developed a parallel method called “RAPID” (rapid acquisition through a parallel imaging design) for imaging the heart on a 0.7T open MRI apparatus, and we have now developed a RAPID head coil and shading correction algorithm for imaging the brain with a 0.4T open MRI apparatus. Images acquired with RAPID were compared with those acquired using a conventional quadrature-detection (QD) head coil.

Materials and Methods: The images were acquired using a dedicated 4-channel RF receiving coil consisting of a solenoid coil and surface coils. For MRI of the brain, we developed 2 methods to acquire the necessary calibration data: a pre-scan method that acquires the calibration data before the main scans and a self-calibration method that acquires the calibration data and imaging data simultaneously. We also modified the algorithm for calculating the shading distribution so that it only uses acquired image data and then corrects the shading.

Results: RAPID was applied for T₁-weighted, T₂-weighted, fluid-attenuation inversion recovery (FLAIR), time-of-flight (TOF), and diffusion-weighted echo-planar (DW-EPI) imaging. The RAPID images had no visible unfolded artifacts or motion artifacts. Images with the same contrast as that with a conventional QD coil were acquired using the RAPID coil and shading correction.

Conclusion: These preliminary results show that RAPID can be applied to imaging of the head using a 0.4T open MRI apparatus.

Keywords: *open MRI, parallel imaging, RF coil, vertical magnetic field*

Introduction

Parallel imaging using multiple array coils has been developed recently and is widely used in clinical diagnosis. Most parallel imaging procedures have been applied on a cylindrical MRI apparatus,¹⁻⁷ and there are a few reports of parallel imaging on an open MRI apparatus.^{8,9} In our previous study, we produced cine parallel imaging of the heart by using a dedicated RF coil on a 0.7T open MRI apparatus.⁹ We termed this imaging technique “RAPID” (rapid acquisition through a parallel imaging design). Imaging of the brain is the most common application of diagnostic MRI, so it

is important to be able to obtain images with contrast similar to that of images obtained using a conventional quadrature-detection (QD) head coil when RAPID is applied. The main difference between a cylindrical and an open apparatus is the direction of the static magnetic field, which is horizontal in the cylindrical apparatus and vertical in the open apparatus. The open apparatus requires an RF-coil structure that is different from that for a cylindrical apparatus because the direction of the static magnetic field is vertical, so the detecting RF magnetic field is horizontal.¹⁰ The legacy RF receiving coil consists of a solenoid coil with a saddle coil that has higher sensitivity than the RF coils for cylindrical MRI, such as a bird-cage resonator (BCR) or slotted-tube resonator (STR). The parallel imaging coil should have a similar sensitivity

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Fig. 1. Structure of the rapid acquisition through a parallel imaging design (RAPID) head coil. The prototype coil consists of 4 surface coils and one solenoid coil. RAPID can be used for both anterior-posterior and right-left directions in the transverse (TRS) section.

Table 1. Specifications of the RAPID head coil

SNR of the MAC mode	Equal to QD head coil
SNR in RAPID with factor of two	$1/\sqrt{2}$ times that of the MAC mode
Image uniformity	More than 50% in each direction

$$\text{Uniformity} = 1 - (P_{\max} - P_{\min}) / (P_{\max} + P_{\min})$$

$P_{\max}$: Maximum pixel value in the image

$P_{\min}$: Minimum pixel value in the image

ty to a high-performance legacy RF coil even at the center of the field of view (FOV). To meet this requirement, we chose a coil structure consisting of one solenoid coil with 2 large-element surface coils and 2 butterfly coils. In a parallel imaging coil, sensitivity distributions of each element coil of the RF receiving coil should differ from the others. For open MRI, parallel imaging is performed under this condition, the sensitivity localization is weaker than that of conventional horizontal-magnetic-field MRI using only surface coils. In addition, a lower magnetic field gives a lower resonance frequency, which typically produces a smaller phase difference between the different RF receiving coils. So, the unwrapping algorithm should be robust for calculation using wrapped data that has a smaller signal change between coils. A more robust unwrapping algorithm is thus required. We have developed a RAPID head coil and a shading correction algorithm. We compared images acquired with RAPID with those acquired with a conventional QD head coil.

Method

We used a 0.4T open MRI apparatus (Aperto®, Hitachi Medical Corporation, Tokyo, Japan) in this study. Figure 1 shows the structure of the RAPID head coil. The solenoid coil produces high sensitivity at the center of the FOV, and the 2 surface coils produce partial sensitivity in the right-left (R-L) direction. Two butterfly coils give partial sensitivity in the anterior-posterior (A-P) direction. By using the solenoid coil, the center sensitivity of the coil is similar to that of a conventional QD head coil. To optimize the RF receiving coil structure for parallel imaging, we designed the coil shape by simulating the RF coil and taking biological load into consideration.^{11,12} As listed in Table 1, the target specification of the RAPID head coil has a similar fundamental signal-to-noise ratio (SNR) (with an acceleration factor of 1.0) to a conventional QD head coil. Four of five coils are selected for the RAPID imaging according to a particular imaging plane and phase-encoding direction. RAPID was thus used for both A-P and R-L phase-

Fig. 2. Imaging using 2 methods for the calibration scan

A: Conventional imaging; **B:** rapid acquisition through a parallel imaging design (RAPID) imaging using the pre-scan calibration mode (PCM); **C:** RAPID imaging using the self-calibration mode (SCM); **D:** The k-space for the SCM data. SCM data were divided into calibration data and reduced field-of-view (FOV) data.

encoding directions for the transverse (TRS) imaging section that is widely used for clinical examination of the brain. We modified the estimation algorithm to obtain the shading distribution of the RAPID coil. Distribution is calculated using function fitting based on the signal in the reconstructed image. This algorithm requires no additional image data. This feature is suitable for open MRI because a volume RF excitation coil typically has low sensitivity in the open MRI to keep a gantry open. The sensitivity distributions of each coil were calculated using the calibration data and then used to unfold the reduced FOV data and to correct the shading. Two methods are used for obtain the calibration data: a pre-scan calibration mode (PCM) that acquires calibration data separately in a pre-scan; and a self-calibration mode (SCM) that acquires calibration data and imaging data simultaneously (Fig. 2).¹³ In RAPID using the PCM (Fig. 2B), a single calibration scan is performed before the main scans (Scan A, Scan B, etc.), and the calibration data is used again for unfolding all the data. In RAPID using the SCM (Fig. 2C), the SCM data set is divided into calibration data and reduced FOV data (Fig. 2D). In this study, we used both of these calibration methods.

In the experiment, the SNR and uniformity of the image were evaluated first with a cylindrical

Table 2. Ratio of SNR for head RAPID using NEMA method

direction	Region					
	A	B	C	D	E	F
A-P	0.70	0.68	0.75	0.66	0.74	0.76
R-L	0.70	0.72	0.79	0.73	0.71	0.73

※1.0 represent MAC mode (RAPID factor = 1.0)

liquid phantom. SNR was measured by using the method of the NEMA (National Electrical Manufacturers Association). Next, the shading and the visible artifact with the head RAPID was evaluated by using T_1 -weighted, T_2 -weighted, and fluid-attenuation inversion recovery (FLAIR) images with a healthy volunteer.

Results

Table 2 lists the ratio of SNR measured in the 6 regions on a cylindrical phantom for SNR measurement. The diameter of the phantom was 165 mm, of region A, 150 mm, and of regions B-F, 20 mm. The measured ratio of SNR for RAPID with an acceleration factor of 2.0 was nearly 0.7 for both A-P and R-L phase-encoding directions. This value is close to the best theoretical value, i.e., 0.71. On the other hand, the calculated uniformities of the sagittal, coronal, and axial sections are 68%, 64%, and 75%, respectively, which sufficiently satisfy our specification in all directions (i.e., 50%).

Figure 3 shows brain images of a healthy volunteer obtained using the QD head coil (Fig. 3A) and the RAPID head coil (Figs. 3B and C). In the case of the RAPID head coil, the image acquired without shading correction has a lot of shading, but the image acquired with the new shading-correction method has no visible shading. Figure 3D shows the sensitivity map obtained using the new shading-correction algorithm, and Fig. 3E shows the signal-intensity profile of each image (Figs. 3A, B, and C) along A-A' line. Applying the new shading correction algorithm results in almost the same profile for the QD head coil (broken line) and the RAPID head coil (solid line). Figure 4 shows T_1 -weighted, T_2 -weighted, and FLAIR images of a healthy volunteer obtained using the QD head coil and the RAPID head coil. An acceleration of 1.5 was simply applied to the standard protocol for the comparison (Fig. 4B). The images obtained using the QD and RAPID coils have the same contrast by using new shading correction algorithm (Figs. 4A and B). Figure 5 shows brain MR angiograms

Fig. 3. Brain images of a healthy volunteer using fluid-attenuation inversion recovery (FLAIR) sequence. (Fast inversion recovery, 2D, transverse [TRS] right to left [R-L], field of view [FOV] = 220 mm, TR/TE = 8500/100 ms, TI = 210 ms, shot number = 27, data matrix = 256×192 , scan time = 230 s). **A:** Image obtained using a quadrature-detection (QD) head coil; **B:** Image obtained using the rapid acquisition through a parallel imaging design (RAPID) coil of the head without shading correction; **C:** Images obtained using the RAPID coil of the head with shading correction; **D:** Calculated sensitivity map; **E:** Signal intensity profile along A-A' line.

(MRA) obtained using the three-dimensional (3D) time-of-flight (TOF) sequence with a conventional QD head coil and with the RAPID head coil (acceleration factor of 1.0). The sensitivity of the RAPID coil is high on both sides of the head near the ears, so the signals from peripheral arteries near the coil were higher with the RAPID head coil than with the QD head coil (indicated by arrow). Figure 6 shows single-shot echo-planar images (EPI; left and center) and single-shot diffusion-weighted (DW)-EPI images (right) using the conventional method (acceleration factor of 1.0; Fig. 6A) and RAPID (acceleration factor of 1.5; Fig. 6B). The images on the left are of a section including the basal ganglia. RAPID improved blurring artifacts by reducing SNR. When RAPID is used, more multi-slice images can be obtained because the echo-train length is shorter for the same spatial resolution. The center images in Fig. 6 are of a section including the supraorbital border. The conventional image may have less distortion than those images obtained with high-field MRI, such as 1.5T MRI. In addition, RAPID improved

blurring artifacts and reduced image distortion. The right-most images in Fig. 6 are DW-EPI images. These RAPID images also show less blurring and distortion. These results indicate that RAPID could be used to diagnose ischemic strokes in brain sections including the basal ganglia or the orbits.

Discussion

In our previous study, we found that cine RAPID of the heart on an open MRI was feasible.^{8,9} In the current study, we performed RAPID of the head with an acceleration factor of 2.0 without causing major artifacts (as described in previous section), but we found that a suitable acceleration factor is 1.5 because of the limitation in SNR on a 0.4T open MRI apparatus. We used a RAPID head coil consisting of 5 coils so that RAPID is realized for both A-P and R-L phase-encoding directions in the transverse image section widely used for clinical brain imaging. In the case of RAPID for the head-foot phase-encoding direc-

Fig. 4. Brain images of healthy volunteer

A: conventional images obtained using quadrature-detection (QD) head coil; **B:** rapid acquisition through a parallel imaging design (RAPID) images obtained using RAPID coil of the head with acceleration factor of 1.5; **a:** T₁-weighted imaging (spin echo, 2D, transverse [TRS] right to left [R-L], field of view [FOV] = 220 mm, TR/TE = 360/13 ms, data matrix = 256 × 160, NSA = 4, scan time = 230/153 s (conventional/RAPID)); **b:** T₂-weighted imaging (fast spin echo, 2D, TRS R-L, FOV = 220 mm, TR/TE = 5000/100 ms, shot number = 22, data matrix = 256 × 224, NSA = 2, scan time = 220/140 s (conventional/RAPID)); **c:** fluid-attenuation inversion recovery (FLAIR) imaging (fast inversion recovery, 2D, TRS (R-L), FOV = 220 mm, TR/TE = 8500/100 ms, TI = 2100 ms, shot number = 27, data matrix = 256 × 192, NSA = 1, scan time = 230/153 s (conventional/RAPID)).

Fig. 5. 3D-TOF using a quadrature-detection (QD) head coil (**A**) and using a rapid acquisition through a parallel imaging design (RAPID) coil (**B**). The images were obtained with conventional imaging (with an acceleration factor of 1.0).

tion, more element coils need to be placed along the head-foot direction. In a cylindrical MRI apparatus, dedicated coils consisting of many surface coils with local sensitivity distribution are used for the

parallel imaging. Shading artifacts and SNR loss therefore appear in the center of the image. A RAPID head coil using a solenoid coil with uniform sensitivity distribution could reduce the

Fig. 6. Brain images for a healthy volunteer obtained by single-shot echo-planar imaging (EPI)/diffusion-weighted (DW)-EPI

A: conventional imaging; **B:** rapid acquisition through a parallel imaging design (RAPID) with an acceleration factor of 1.5; left: section including the basal ganglia; center: section including the supraorbital border; right: images obtained using the DW-EPI sequence in the same section from which the center images were obtained. (Single shot DW-EPI, 2D, transverse [TRS] right to left [R-L], field of view [FOV]=280 mm, TR/TE=6000/107.3 ms, shot number=1, data matrix=128×80, b-value=700 s/mm², scan time=6 s).

shading artifact and improve the center SNR. In parallel imaging, it is important for unfolding that the sensitivity distribution of the RF receiving coil differs from one channel to another. The possibility of a shading artifact in images obtained using a RAPID coil is therefore of great concern. In a cylindrical MRI apparatus, a transmitting and receiving (T/R) coil with an almost uniform sensitivity distribution is usually used for reference data to compensate for this shading artifact. In this study, we developed a reconstruction algorithm to calculate the shading distribution without the need for any additional reference data. Note that this algorithm cannot be used to correct each image separately for such applications as 3D and diffusion-weighted imaging, which treat the image as series data. For such applications, shading correction can be used to keep the data in the series continuous by selecting reference data in each series and using it to calculate the shading (for example, one data point is selected as reference data in the slab in the 3D imaging, and the data for $b=0$ is selected as reference data in the diffusion-weighted

imaging). As a result, RAPID images had no shading artifacts and had similar contrast as images obtained using the QD coil on an open MRI without a T/R coil. Because the calibration data needed when RAPID is used are additional data, it is important to reduce the amount of calibration data as much as possible to keep the scan time short. We thus developed 2 methods for the calibration scan. In the case of PCM, only reduced FOV data is acquired, and RAPID thus shortens the imaging time most efficiently. This method is most suitable for imaging regions without motion, such as the brain, and for imaging the same section repeatedly with different sequences to obtain images with different contrast, such as T_1 -weighted, T_2 -weighted, FLAIR, and DW-EPI images. The scan time is longer for SCM, which is a suitable calibration method when the imaged section is changed during the scan, the number of slices is high, or the imaged region contains motion caused by breathing (as cardiac and abdominal regions do). Parallel imaging by the lower static magnetic field has a limit because many pulse sequences are

used with more than 2 summations. For these pulse sequences, acquisition time is normally shortened by just performing a single acquisition. Hence, for imaging the brain, single-shot DWI, TOF, and T_1 -/ T_2 -weighted imaging have sufficiently high SNR. In some cases, therefore, parallel imaging may be useful in clinical cases. The peripheral imaging also has high SNR, so parallel imaging seems preferable. Clinical feasibility tests on the peripheral parts are planned in near future.

Conclusion

We have developed a RAPID head coil and a shading correction algorithm for imaging the head using a 0.4T open MRI apparatus. We used them to obtain images with the same contrast as those obtained using a conventional quadrature-detection head coil. Preliminary testing showed that RAPID reduces the image distortion caused by the susceptibility of the magnetic field in EPI.

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